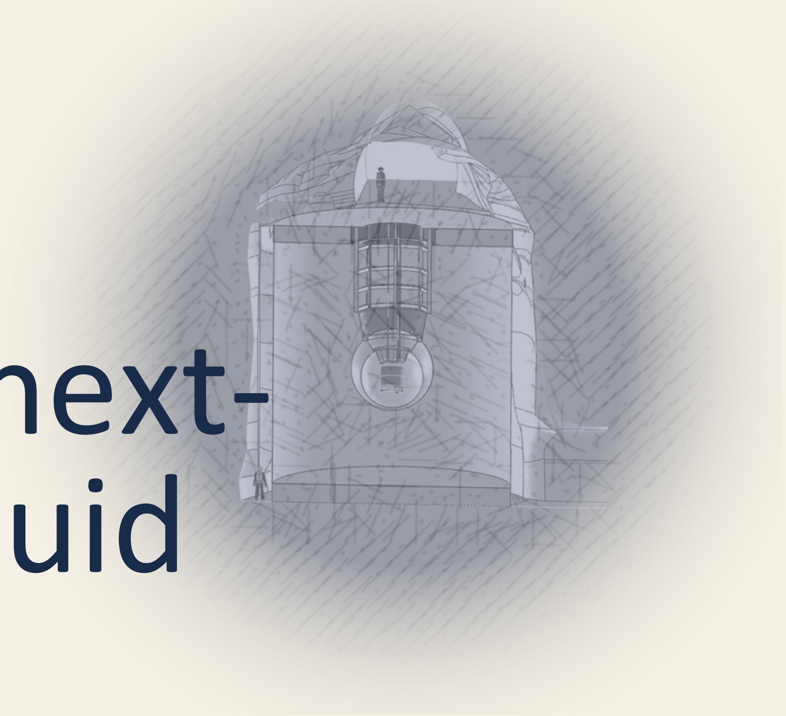


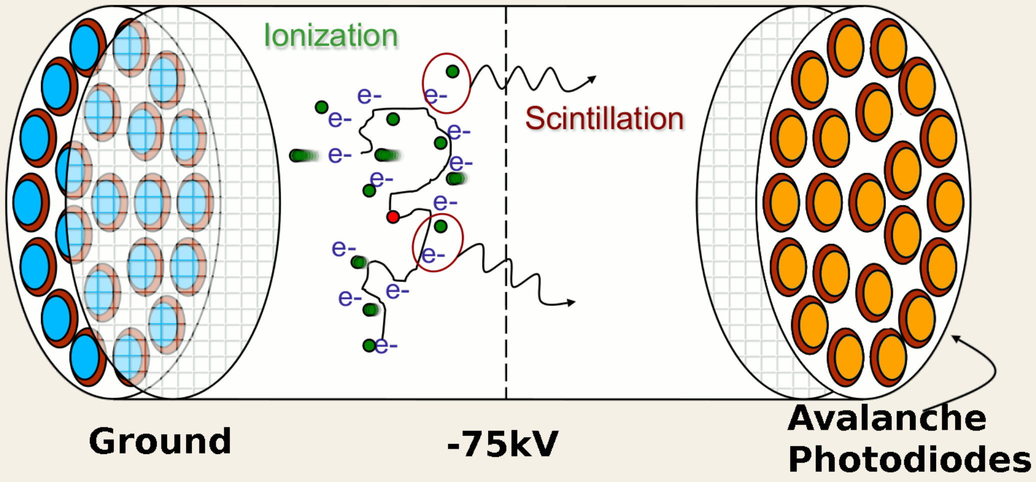
Technologies for the next-generation noble liquid detectors

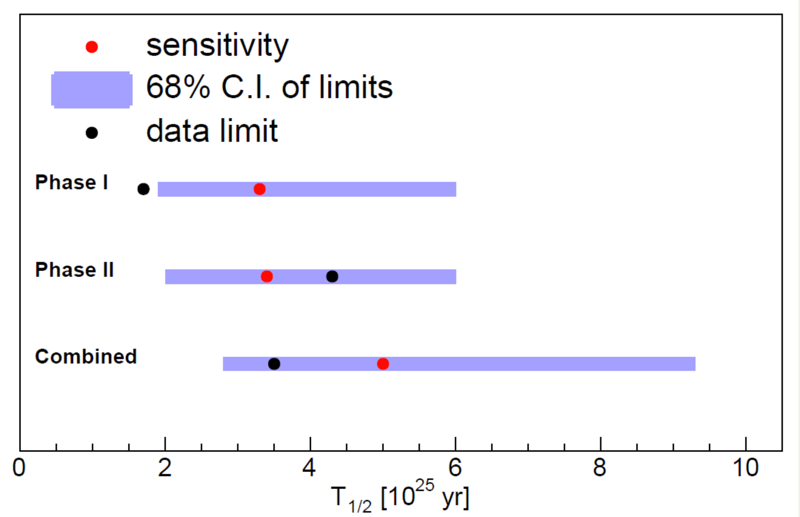
Zepeng Li, UC San Diego

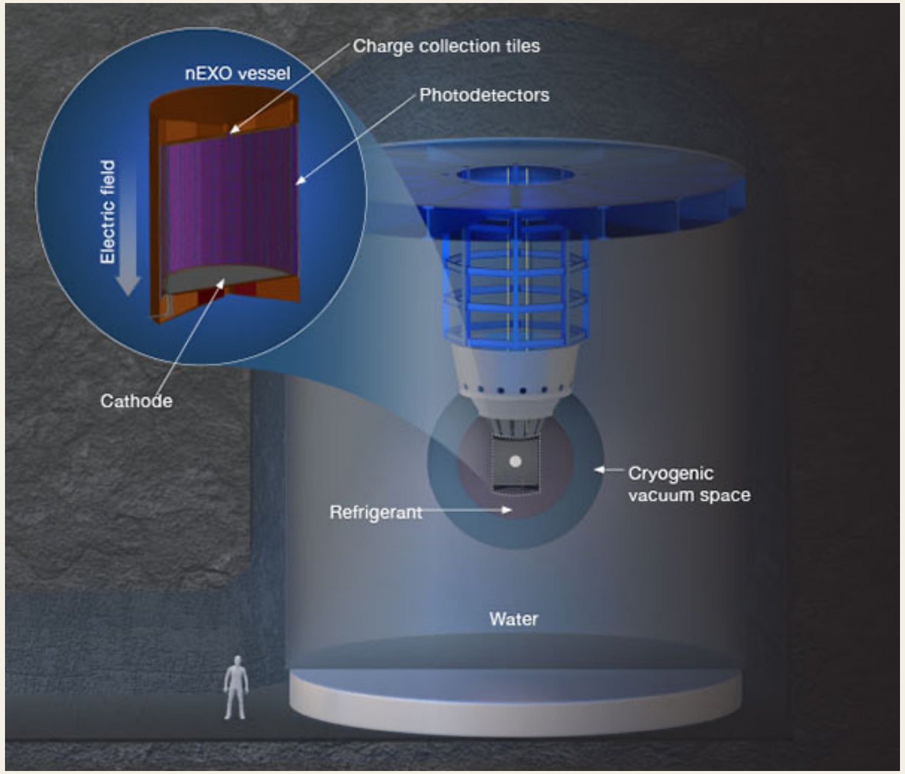
Apr 3, 2024

UHM Physics and Astronomy

Noble liquid detectors for new physics searches







Liquid xenon (LXe) time projection chamber (TPC) has demonstrated its great capability in search for neutrinoless double beta decay!

$0\nu\beta\beta$ searches

2023 Nuclear Physics Long Range Plan: As the highest priority for new experiment construction, we recommend that the United States lead an international consortium that will undertake a neutrinoless double beta decay campaign, featuring the expeditious construction of ton-scale experiments, using different isotopes and complementary techniques.

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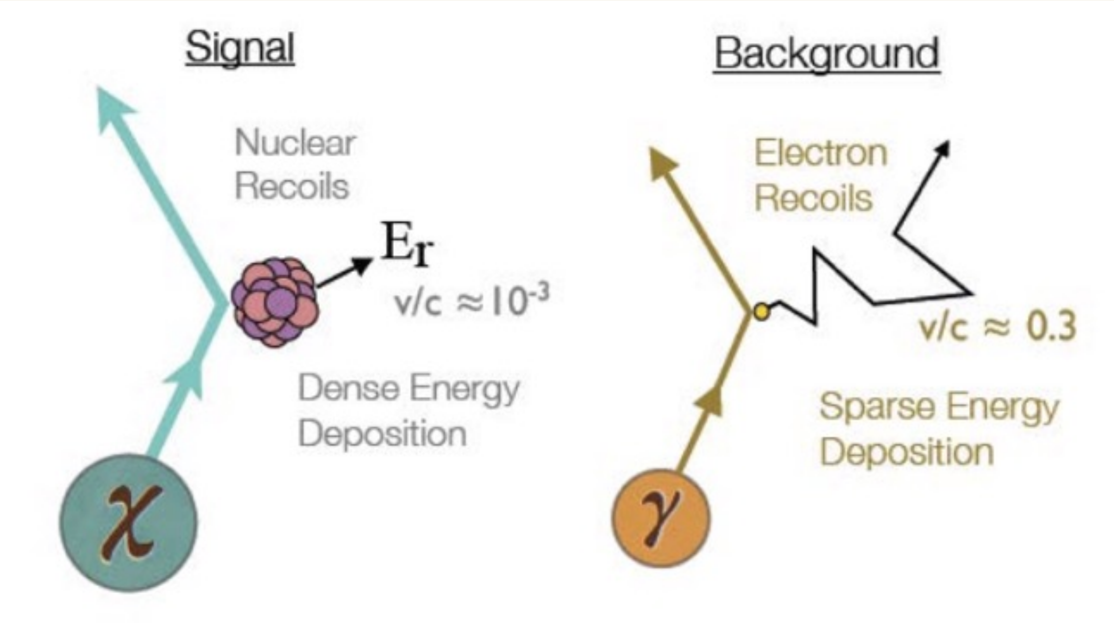
Noble liquid detectors for new physics searches

LZ

XENONnT

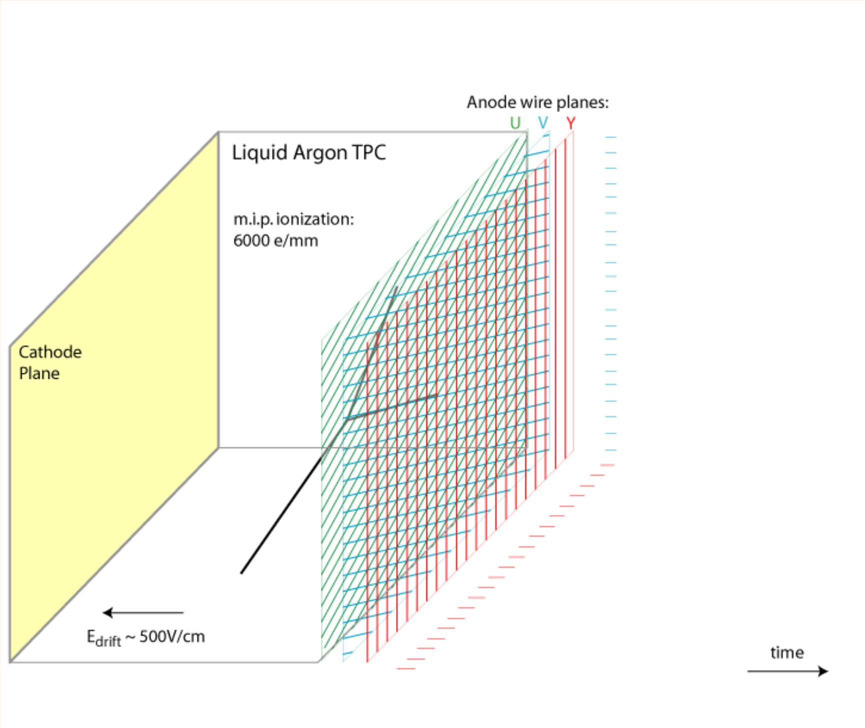
"Direct Detection"

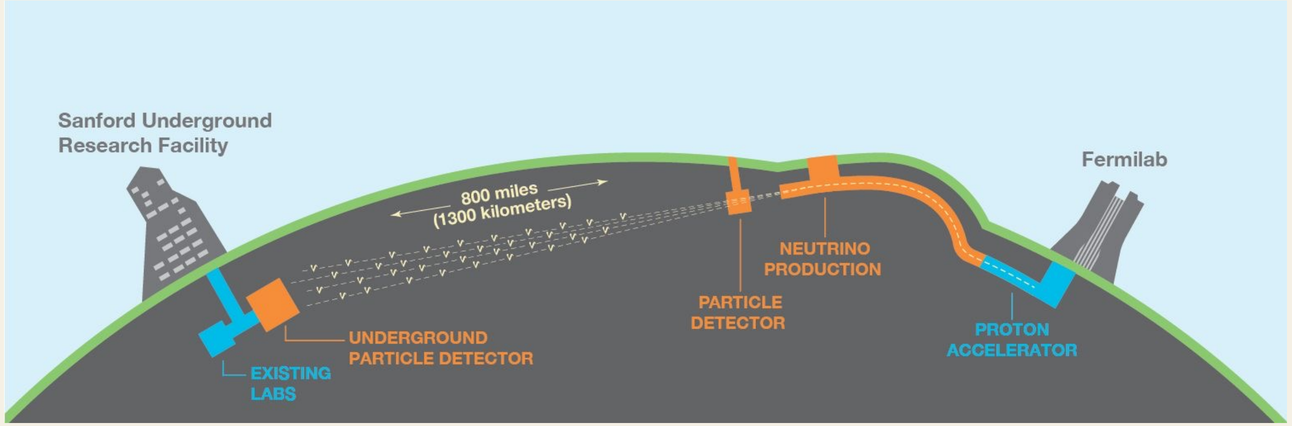
Scattering of dark matter from nuclei



LXe TPC has produced the most sensitive WIMP search!
Low energy threshold LXe TPC also opens opportunity for neutrino detection

Liquid argon TPC for neutrino experiments





DUNE

New technologies for $0\nu\beta\beta$ search with LXeTPC

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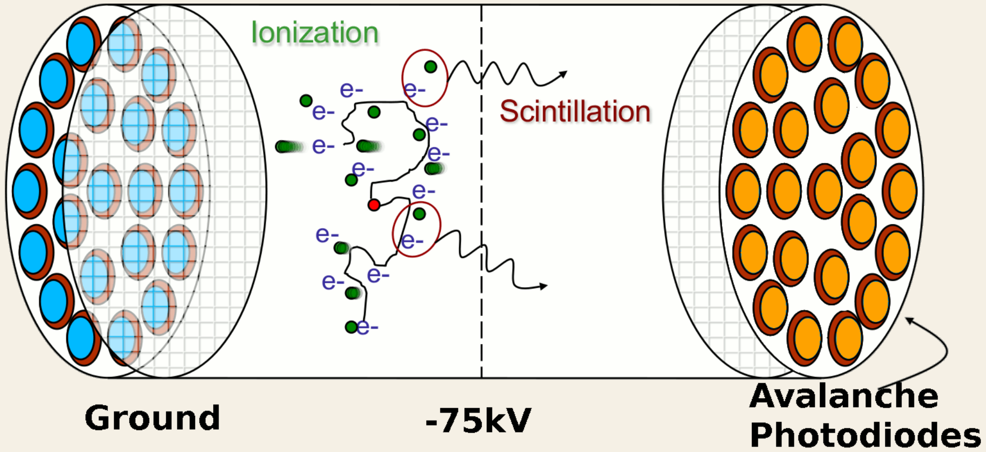
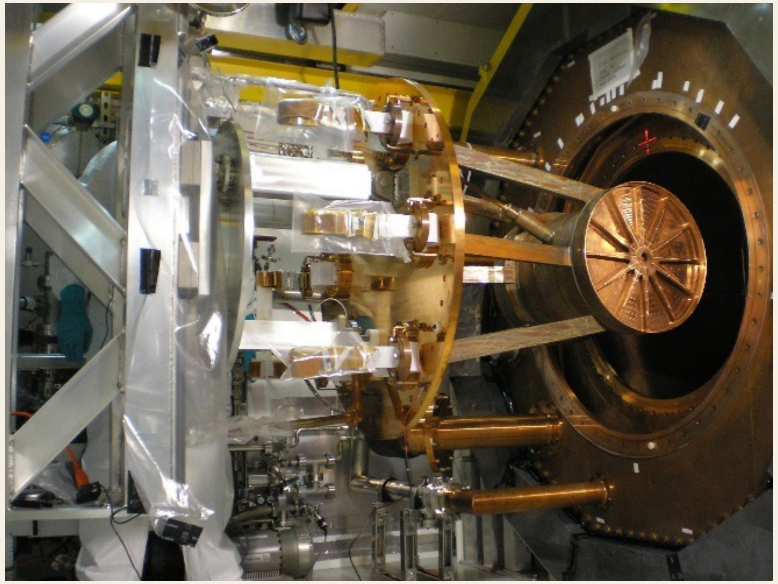
Search for $0\nu\beta\beta$ decay with liquid xenon time projection chamber



- EXO-200 operational between 2011 and 2018
- 175 kg **enriched** liquid xenon (LXe)
- **Low radioactivity** in LXe and strong **self-shielding**
- **Good energy resolution** at Q value of 2.5 MeV
- 2D readout of ionization charge and scintillation light to achieve **full 3D event reconstruction**



- Discovered 2νββ decay of ^{136}Xe (PRL 2011)
- First 0νββ result (Nature 2014)
- Final 0νββ with $T_{1/2} > 3.5 \times 10^{25}$ yr (PRL 2019)
- Multiple leading limits on other decay modes of ^{136}Xe and ^{134}Xe

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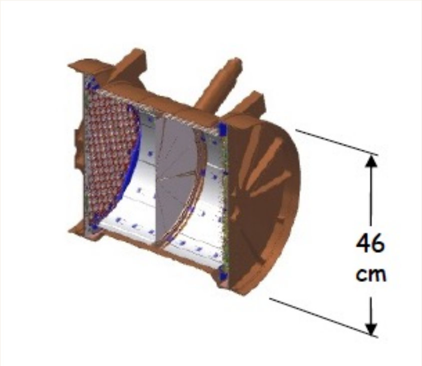
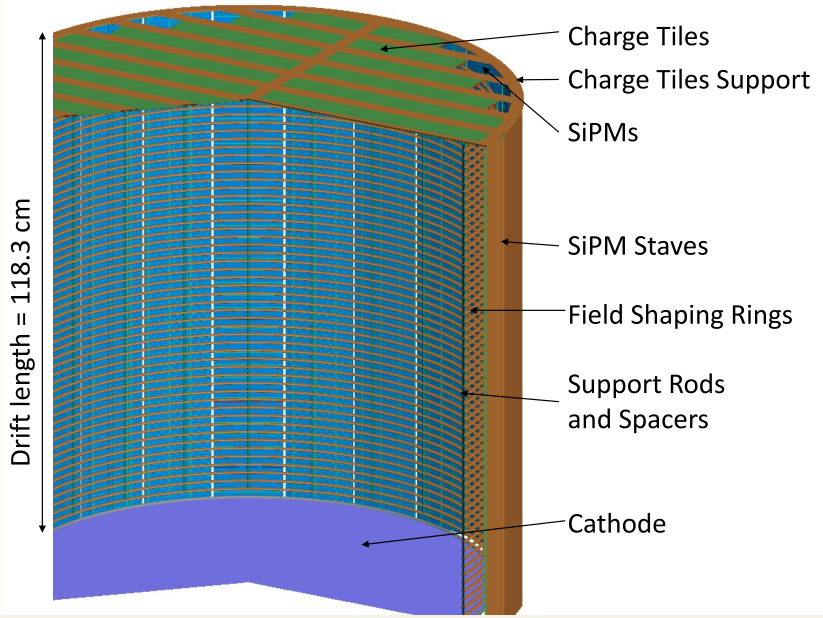
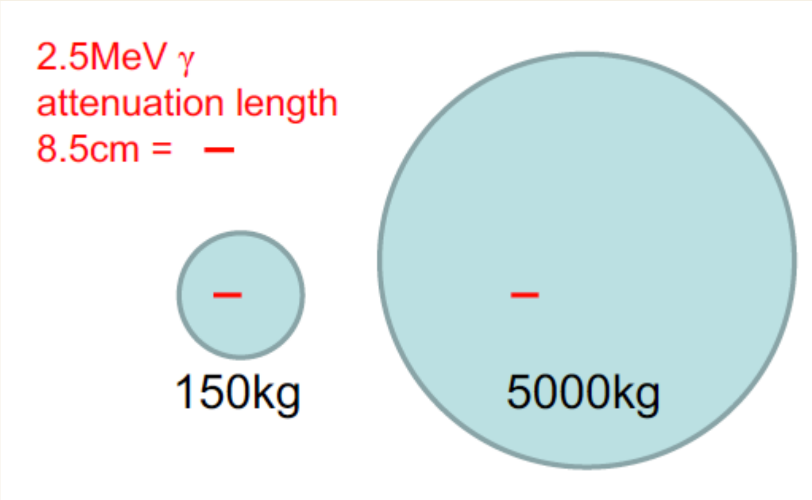
Scaling up from EXO-200 to nEXO



- More ^{136}Xe: 175 kg → 5000 kg
- More shielding: active water shield
- Larger overburden: 2000 m underground
- Upgraded instrumentation: SiPMs for light, charge tiles for ionization electrons, cold ASICs for readout
- Homogenous detector: better self-shielding





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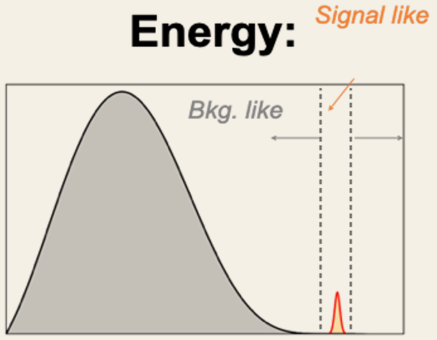
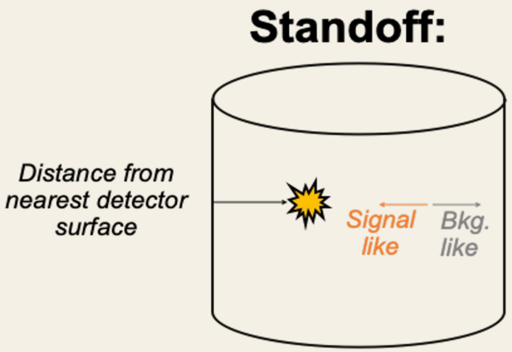
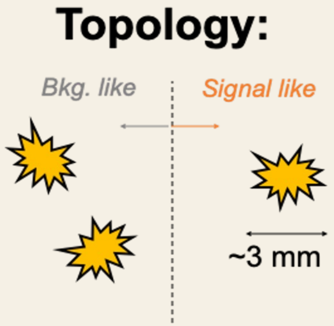
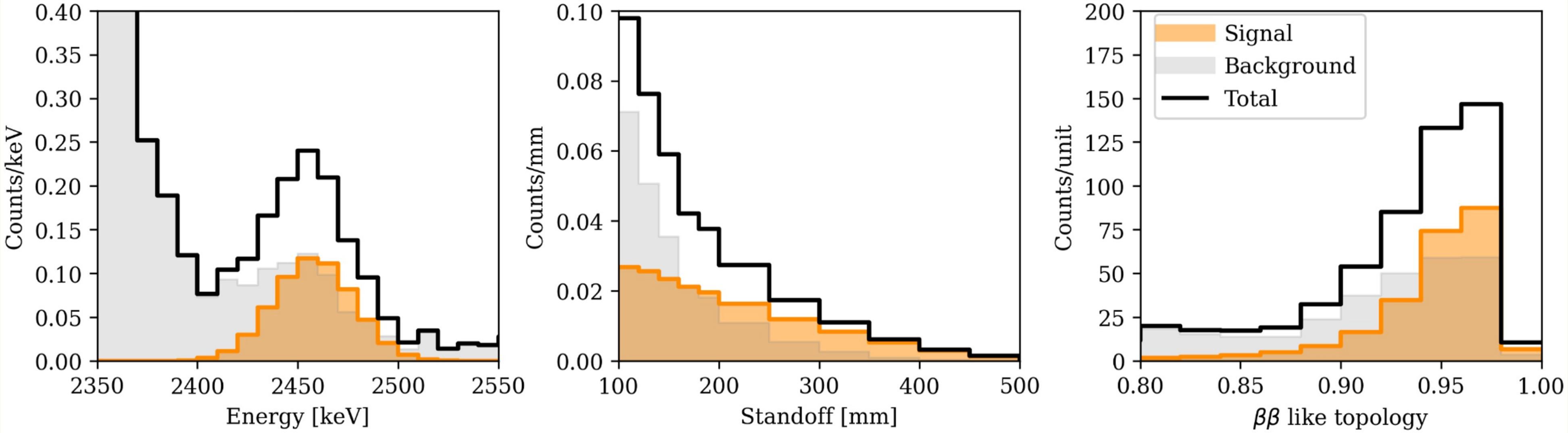
nEXO signal and background







1D projections of simulated nEXO signal and backgrounds



Assumed signal: $T_{1/2} = 7.4\times10^{27}$ year

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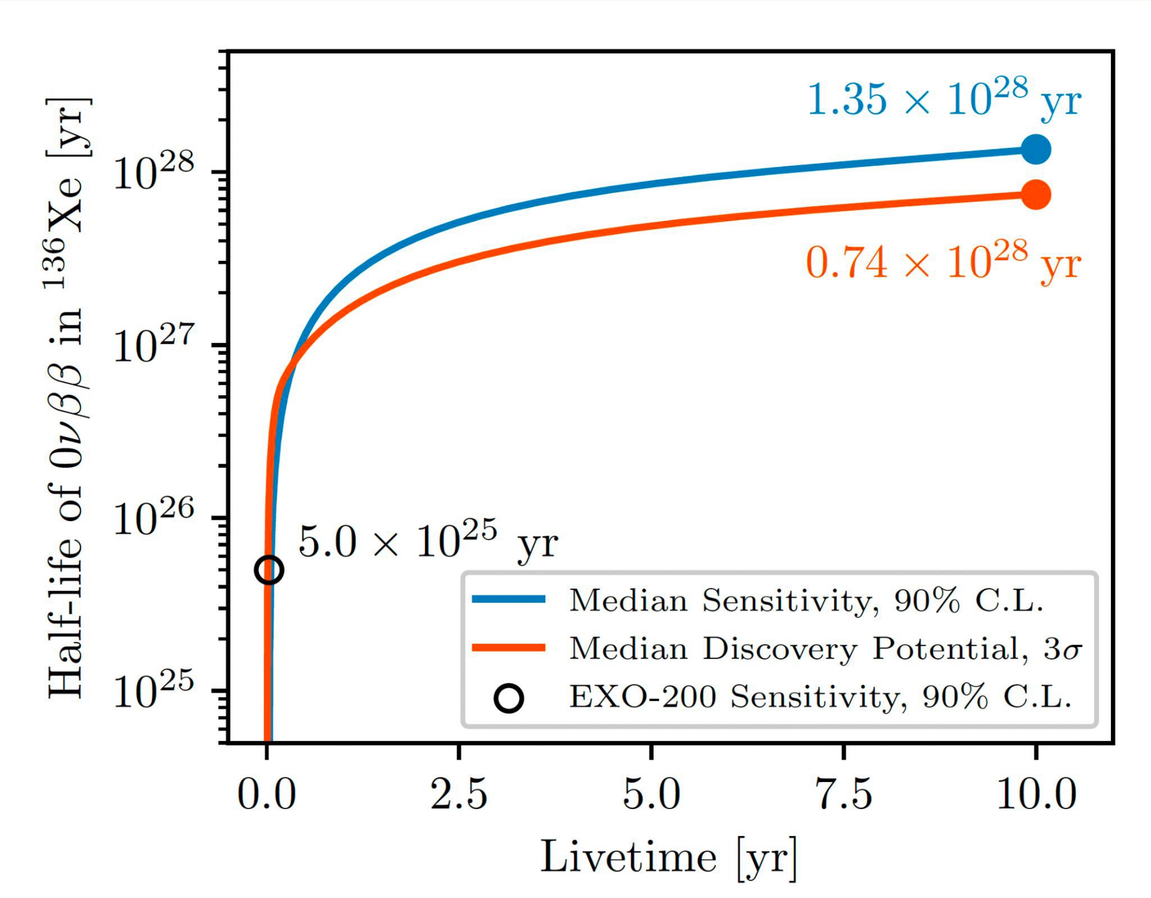
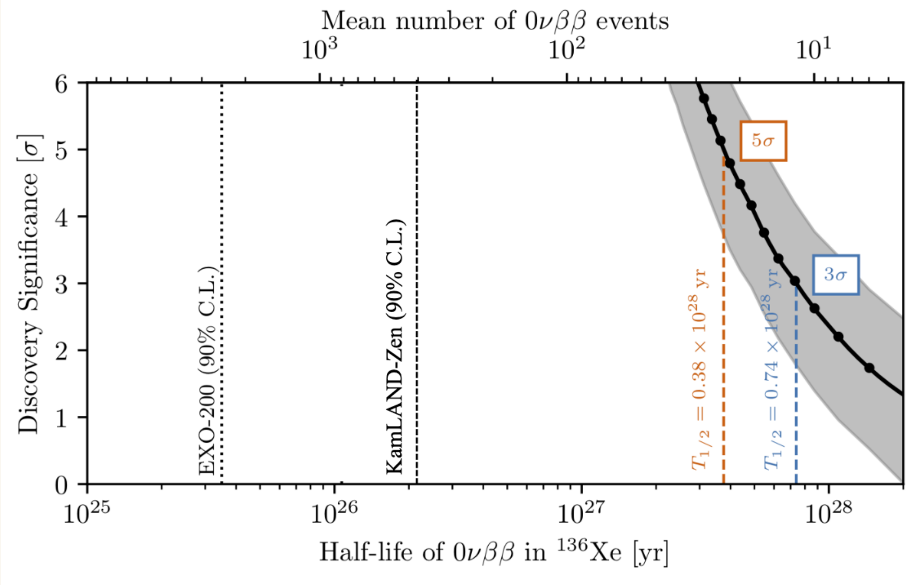
Projected $0\nu\beta\beta$ halflife sensitivity



- Can discover $0\nu\beta\beta$ halflife of **0.74 x 10^{28} yrs at 3σ significance**
- Can exclude $0\nu\beta\beta$ halflife of **1.35 x 10^{28} yrs at 90% CL,** 2 orders of magnitude higher than the current best lower limit



Adhikari et al., J. Phys. G 49 (2022), arXiv:2106.16243

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My contributions to EXO-200/nEXO

- Innovative instrumentation R&D for low background, good energy resolution
  - Charge readout system
  - nEXO charge readout simulation (JINST 14 2019)
  - Photon readout system
  - Barium tagging
- Machine learning (ML) algorithms to facilitate the discovery of new physics
  - Deep learning algorithm for nEXO background rejection (JINST 14 2019)
  - ML algorithm to produce simulations (JINST 18 2023)
  - Search for $2\nu\beta\beta$ of ^{136}Xe to the excited state of ^{136}Ba (Chin.Phys.C 47, 2023)
  - EXO-200 ML data release
  - ML implementation on FPGA for fast inference
- Physics analyses with complete EXO-200 dataset
  - Majoron emitting $\beta\beta$ search (Phys. Rev. D 104 2021)

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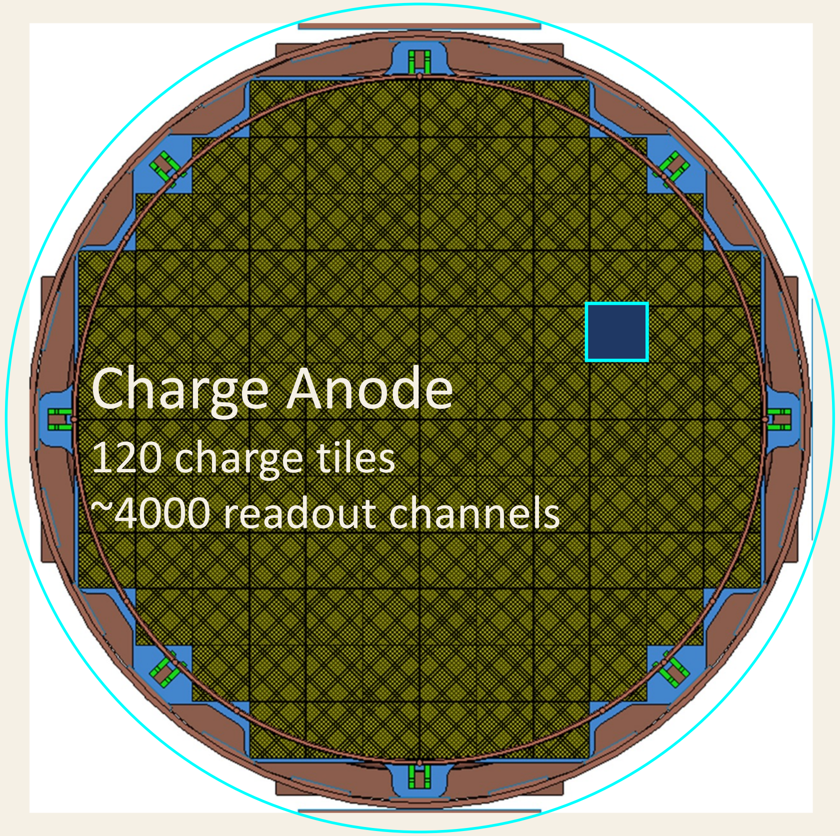
Instrumentation R&D

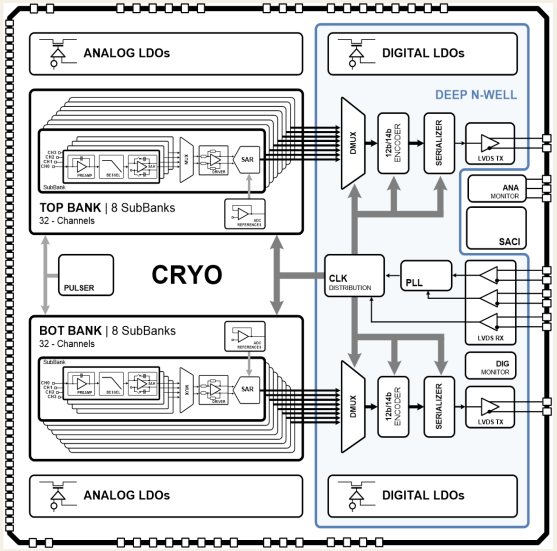
Instrumentation R&D in P5 report

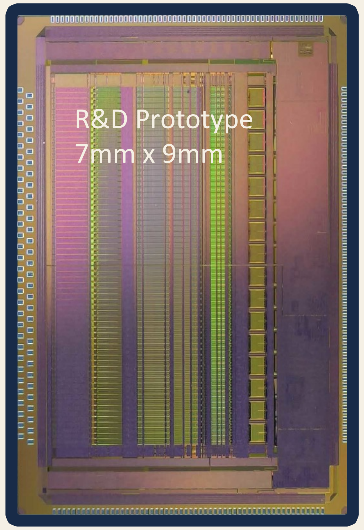
The particle physics community has identified the need for stronger coordination between the different groups carrying out detector R&D in the US. We strongly support the R&D Collaborations (RDCs) that are being established and will be stewarded by CPAD, the Coordinating Panel for Advanced Detectors, overseen by the APS/DPF.

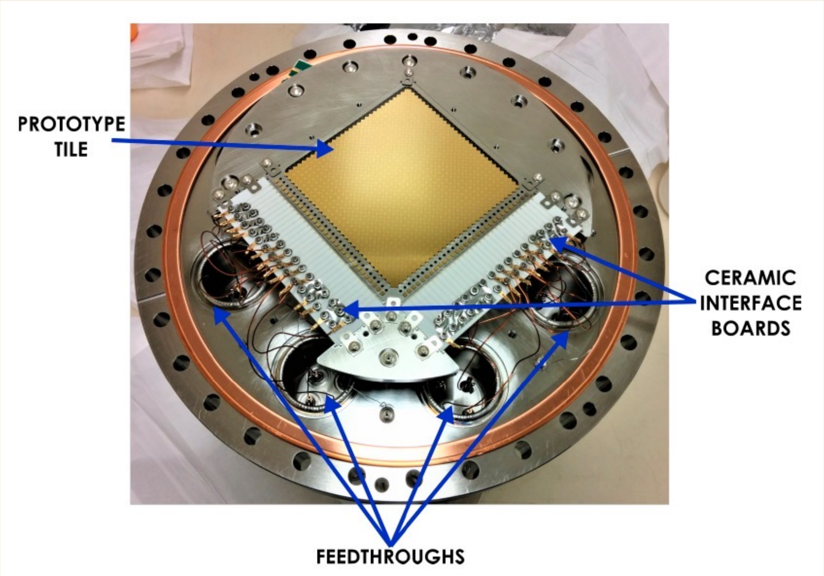
Instrumentation R&D: charge



Charge signals are collected by the sensing strips on tiles, and are amplified, digitized and transmitted to DAQ by CRYO ASIC







A prototype tile tested in LXe JINST 13 P01006

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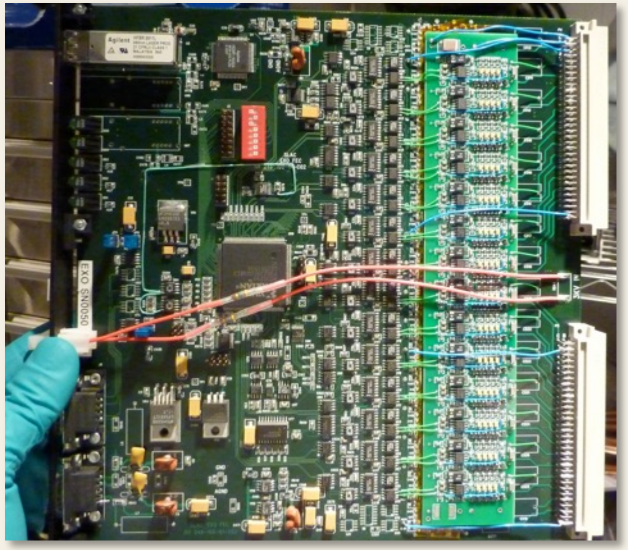
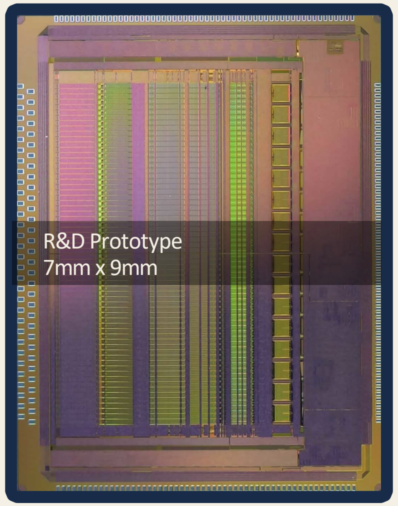
Instrumentation R&D: charge



EXO-200 front end board
- COTS components
- 16 channels
- Size: 20 cm x 20 cm



nEXO CRYO ASIC
- R&D prototype
- TSMC 130 nm
- 64 channels
- Size: 0.7 cm x 0.9 cm

Advantages of custom ASIC:

- **Lower radioactivity**: using ASIC can significantly reduce the amount of material used. ASIC itself is tested to be extremely radiopure
- **Better chemical purity** : reducing the number of components, packaging, and interconnections will reduce the electronegative impurity in LXe
- **Lower noise**: better energy resolution

Drawbacks:

- Higher development cost
- Longer R&D and testing time

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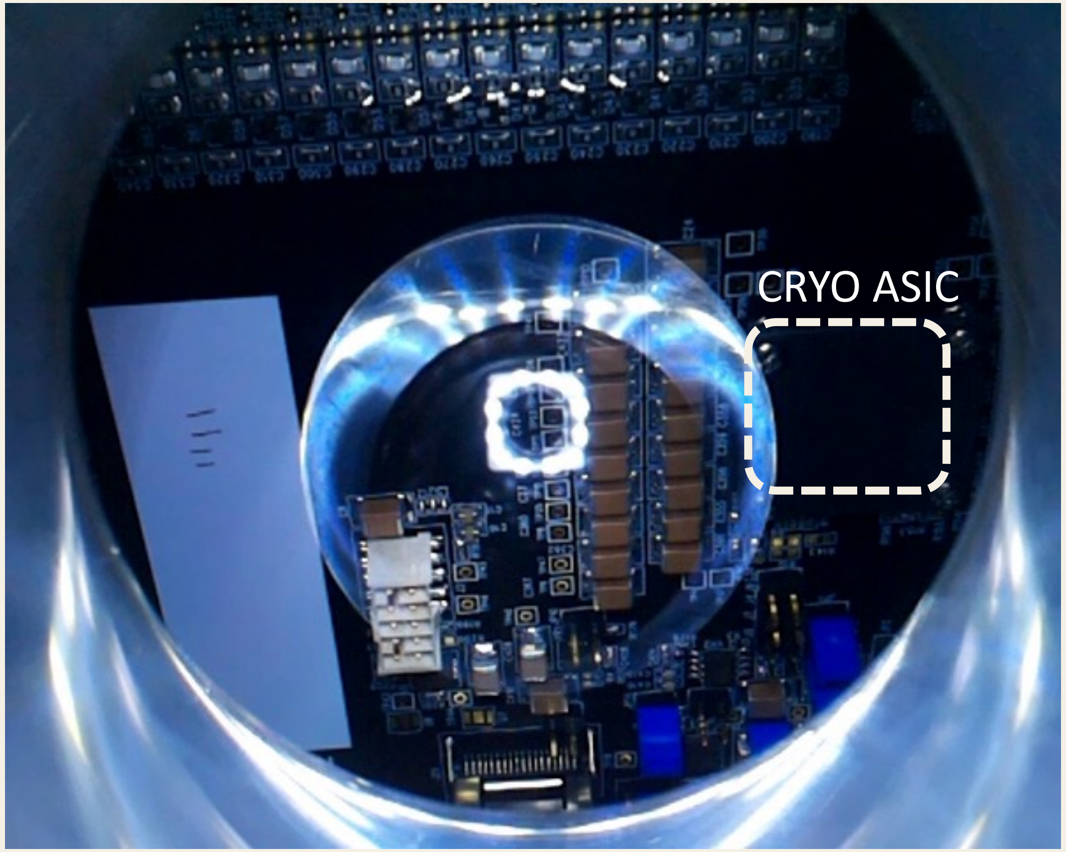
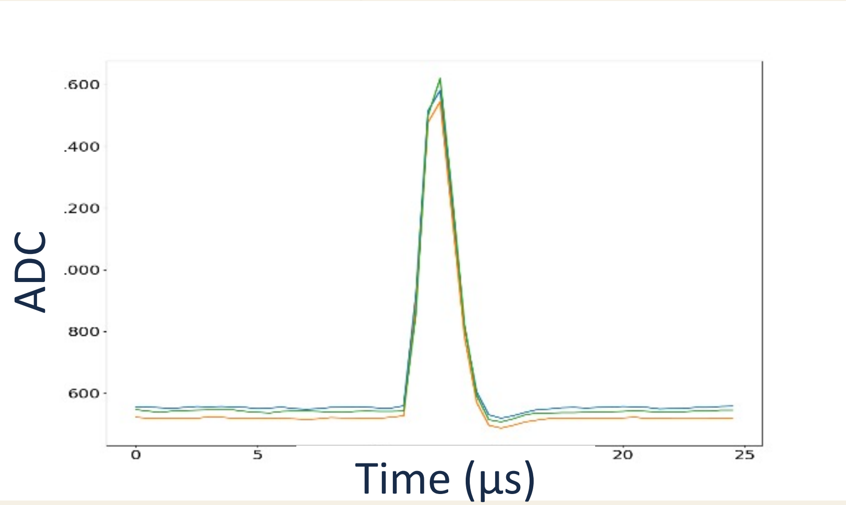
My contribution to R&D of charge readout

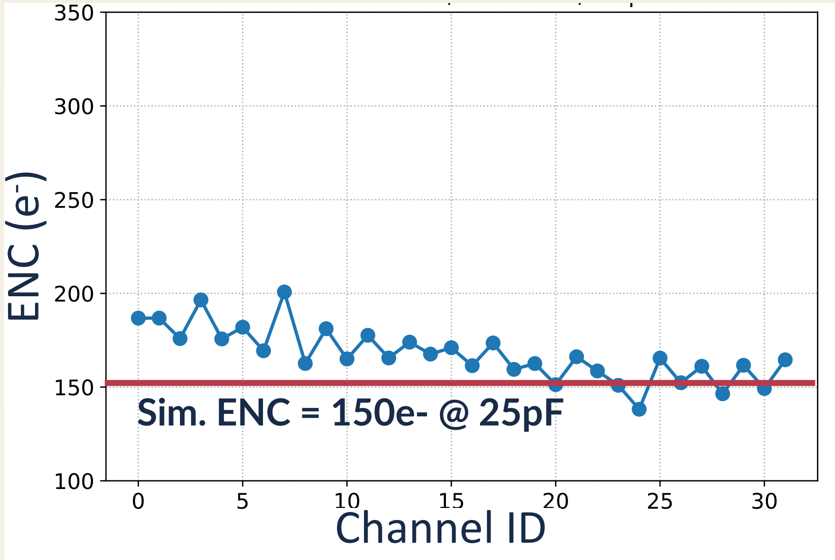


First demonstration of full function in LXe

Sample charge injection in LXe



Noise measurement in LXe



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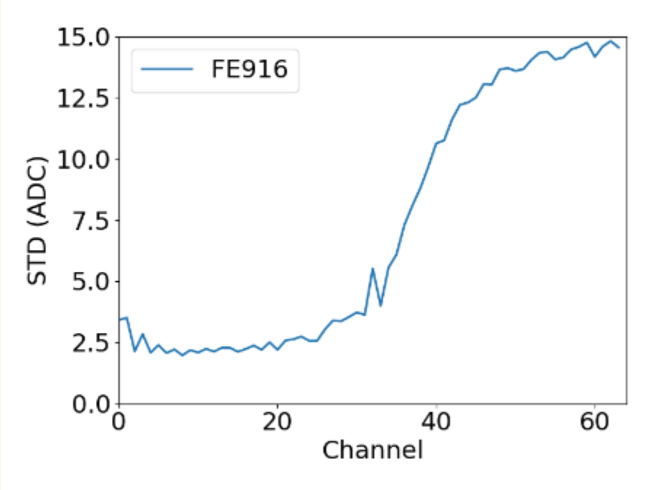
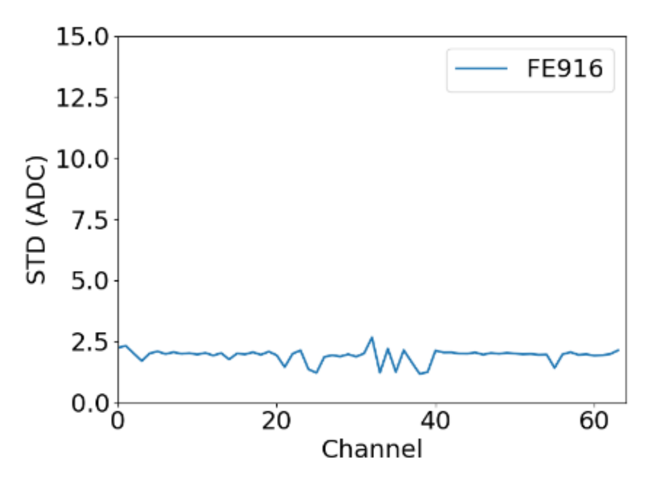
My contribution to R&D of charge readout





- Quantitively measure the conditions of xenon boiling due to ASIC
- Measured microphonic noise from xenon boiling
- Boiling mitigation by pressurizing the chamber

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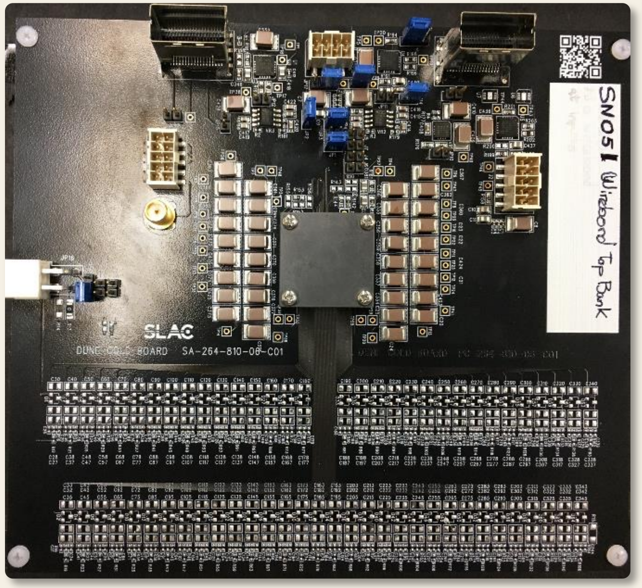
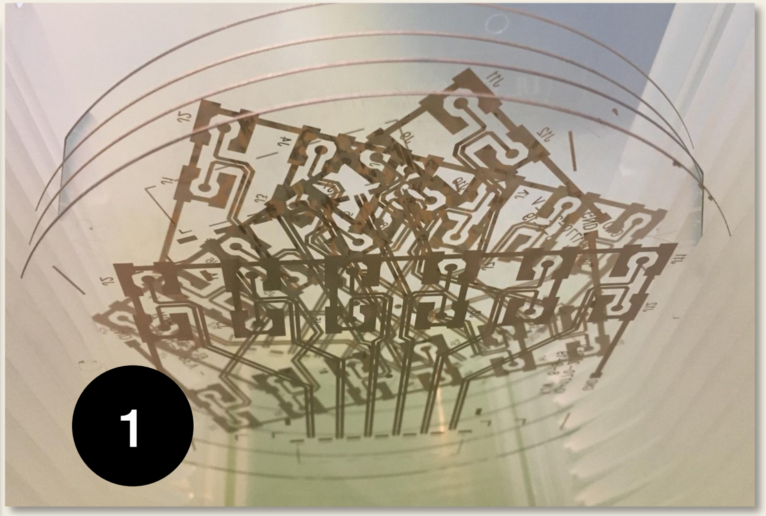
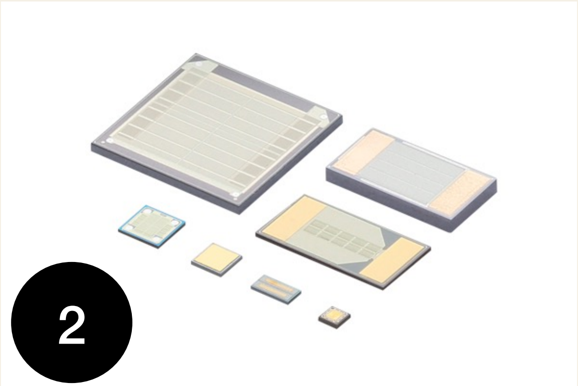
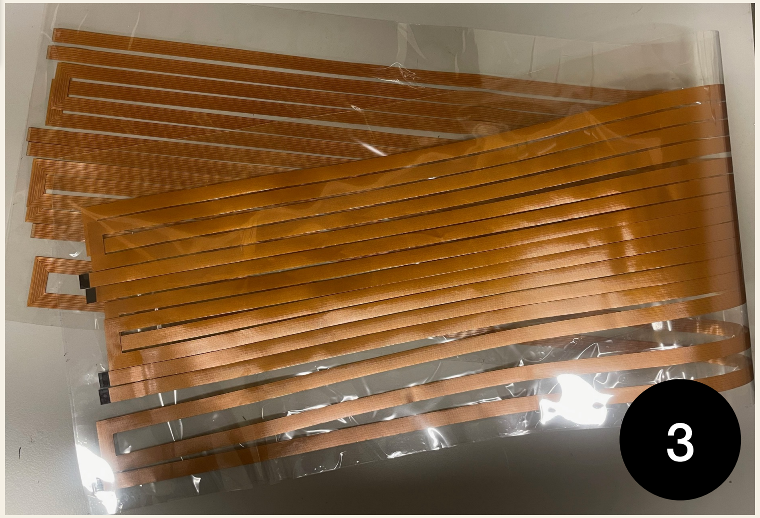
My contribution to R&D of charge readout



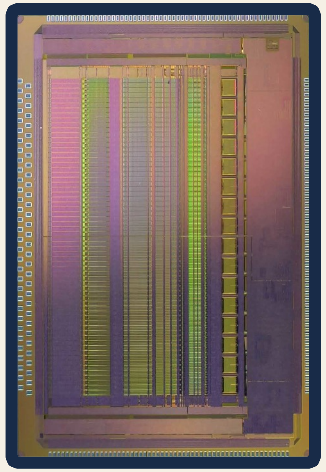


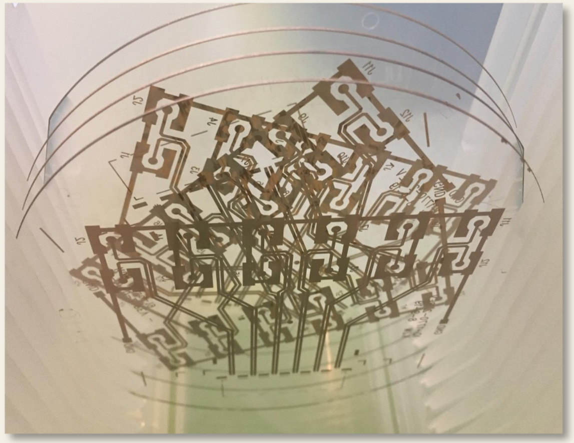


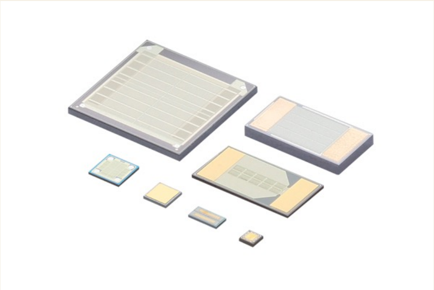


- Fewer capacitors on ASIC board as required by future fused silica board
- Test ASIC with µF capacitors to be replaced with silicon ones in nEXO
- Characterization of silicon capacitor: breakdown voltage, leakage current
- Data transmission with long flex cable with the same design of nEXO cable

R&D needs for nEXO charge readout

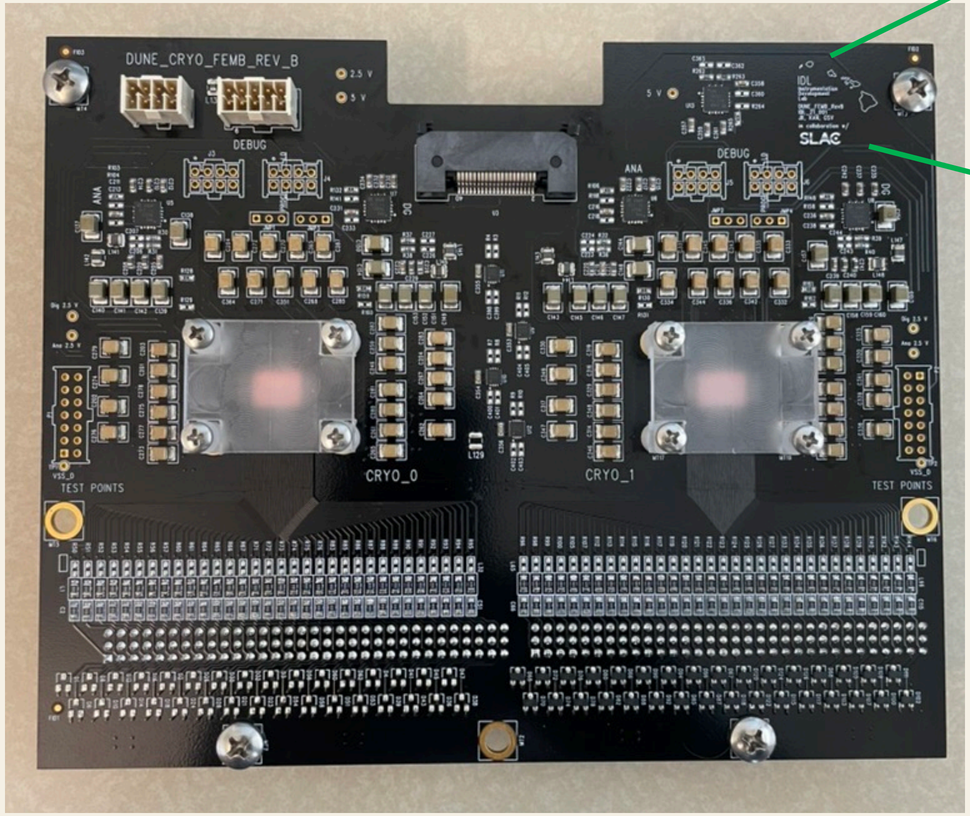






- Develop and characterize new CRYO ASIC
- Integration of charge readout system with ultra-pure components and achieve noise requirement in LXe
- Integration of charge readout system and charge tile

Some connection with Hawaii



The Design, Characterization, and Testing of the CRYO ASIC Front End Motherboard

for the Deep Underground Neutrino Experiment

A THESIS SUBMITTED TO THE GRADUATE DIVISION OF THE UNIVERSITY OF HAWAIʻI IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

IN

ELECTRICAL ENGINEERING

October 2021

By

Jeffrey B Kleyner

Dissertation Committee:

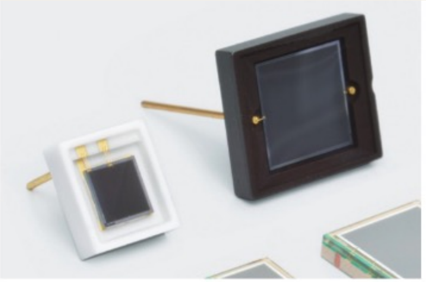
G. Varner, Chairperson

K. Nishimura

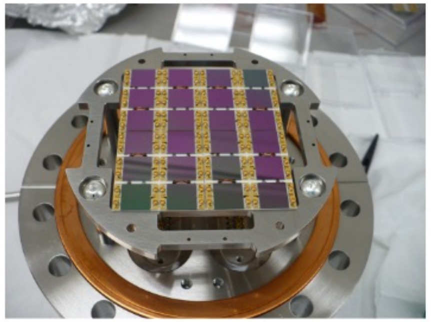
A. Ohta

Different versions of ASIC loaded on the board for external calibration, new digital signal driver test, and SiPM readout

Instrumentation R&D: light

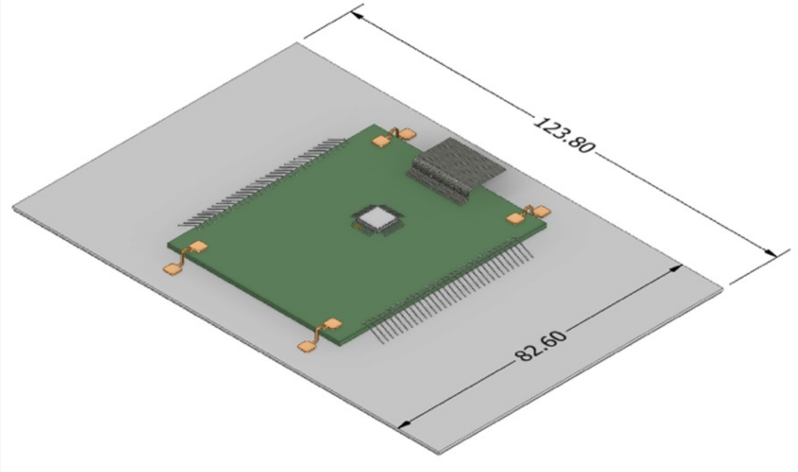


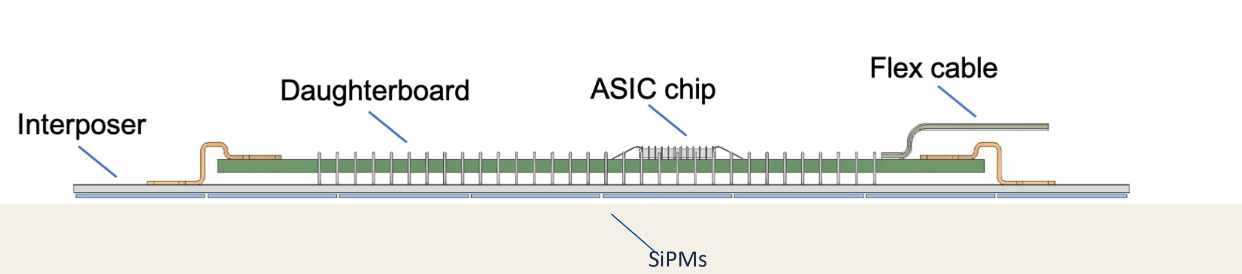
SiPM 1 x 1 cm^2



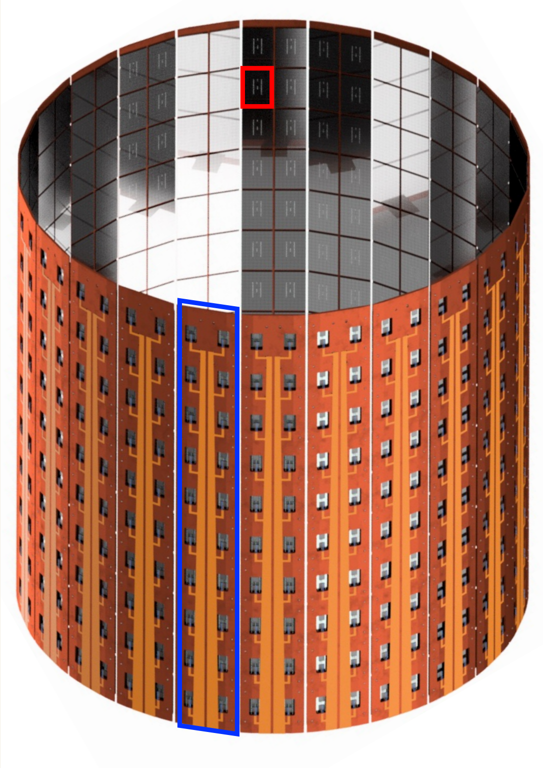
SiPM array R&D

Grouped in 6 cm^2 sub-arrays





Tile module of 16 sub-arrays with integrated ASIC. 20 tiles make up a stave.



24 staves surround the barrel 4.6 m^2 photo-coverage and 7680 channels

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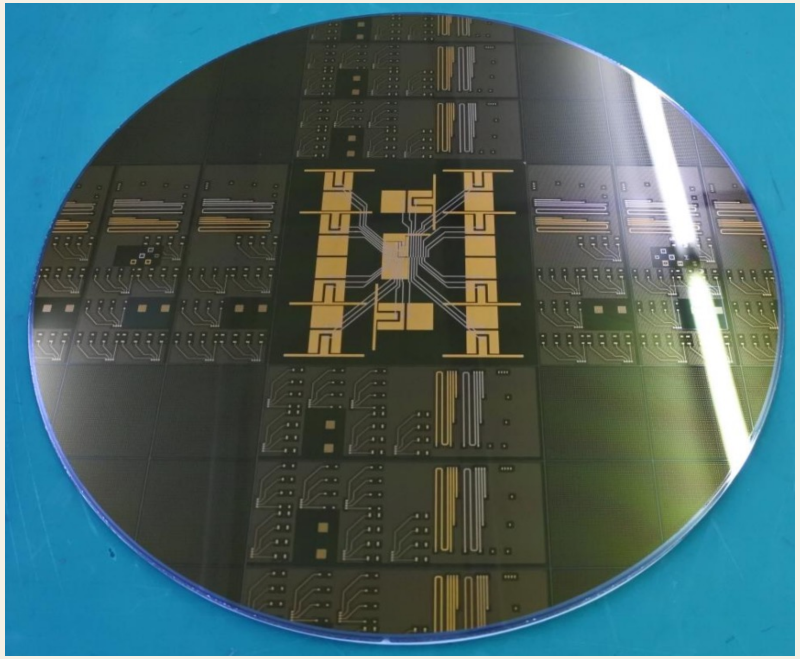
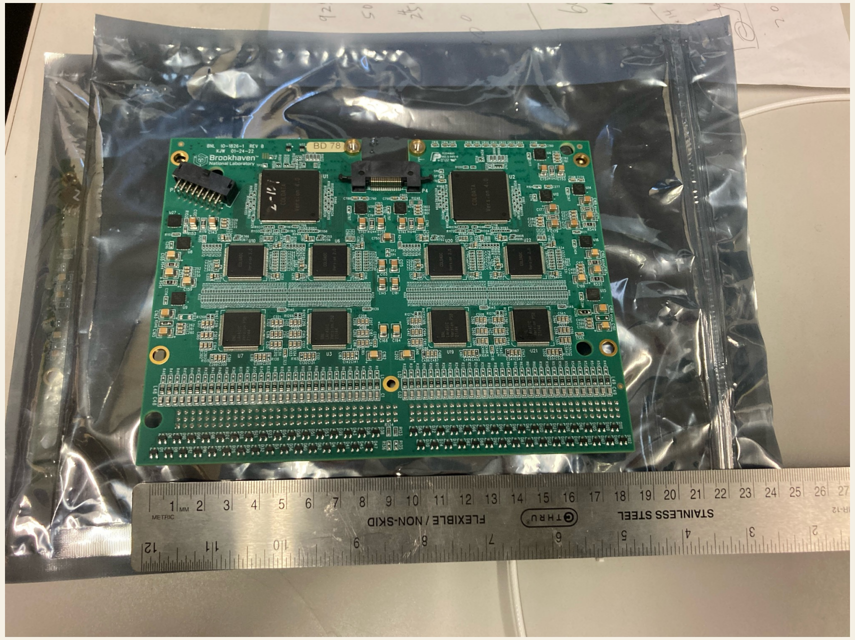
My contribution to R&D of light readout



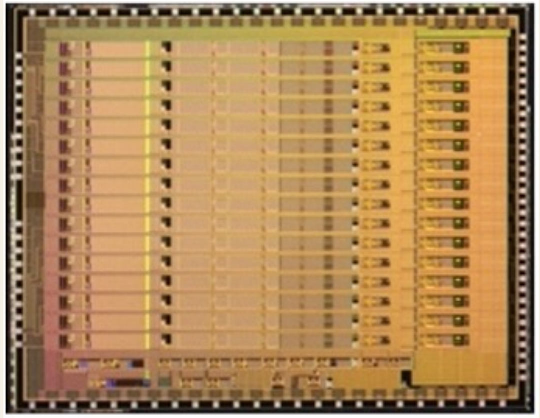
In collaboration with IHEP to test SiPM array on a silicon interposer in LXe

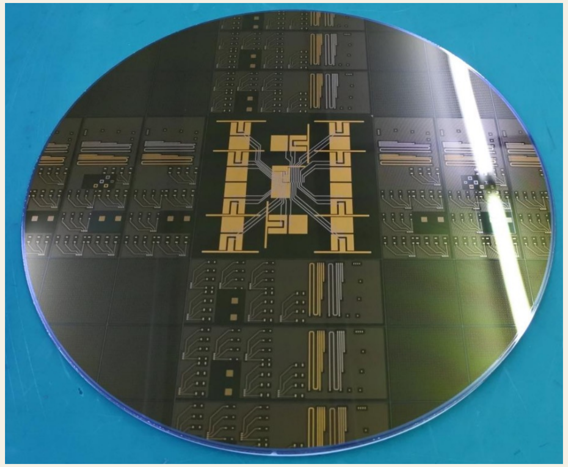


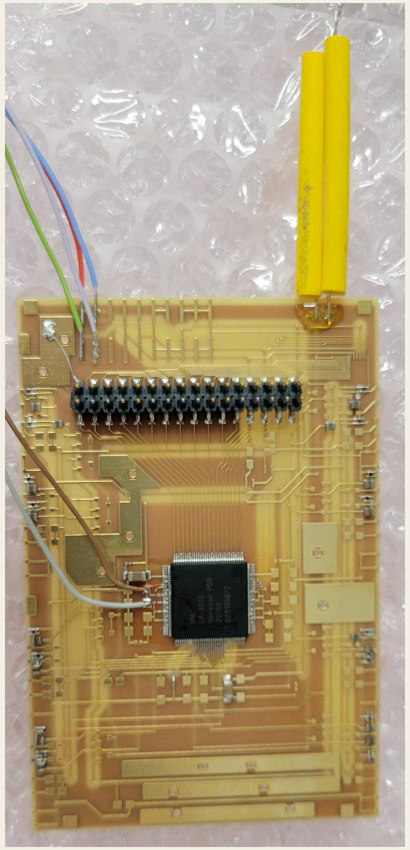
In collaboration with BNL to test LArASIC for SiPM readout in LXe

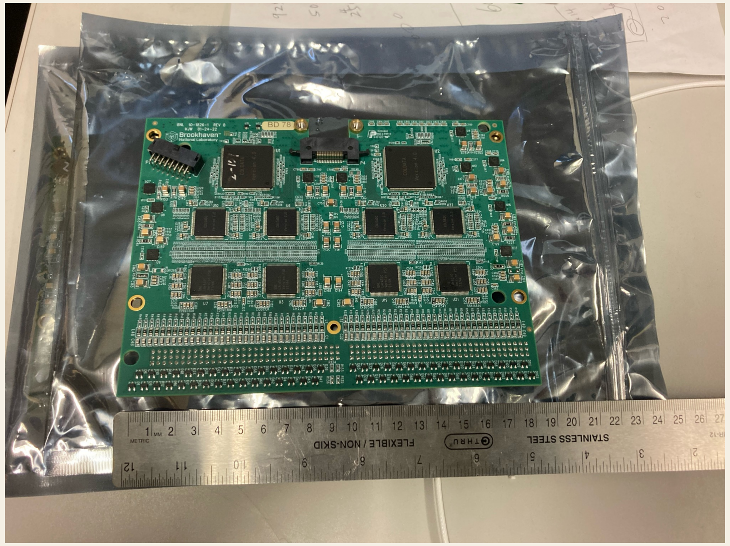
- Two subsystems will be tested separately and tested together afterwards
- Demonstration of two key technologies in photon readout system

R&D needs for nEXO light readout







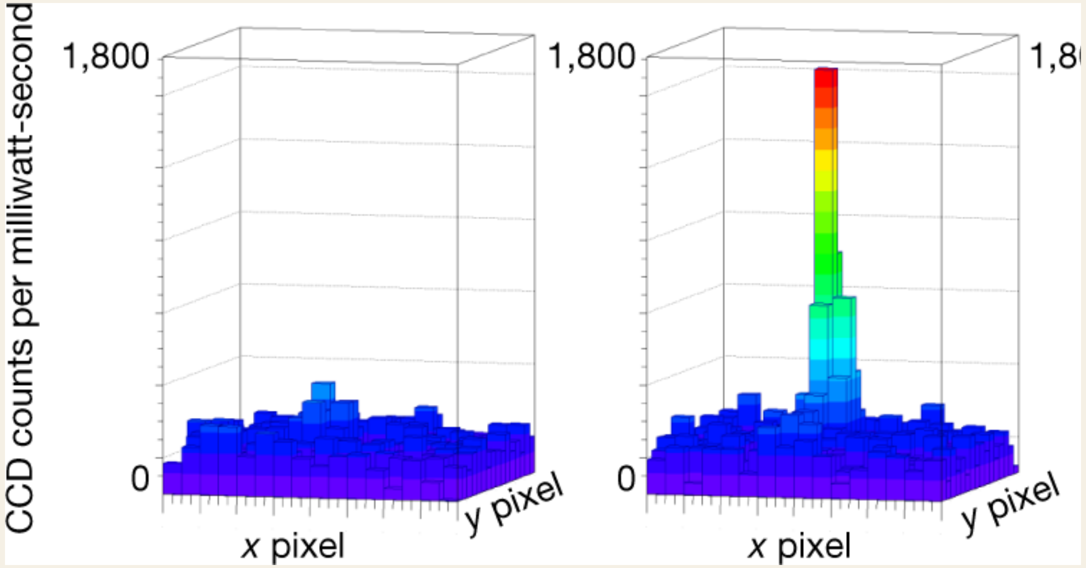


- Test bare silicon die in liquid xenon
- Integrate LArASIC onto a fused silica PCB
- Integrate full chain light readout system and test it in LXe

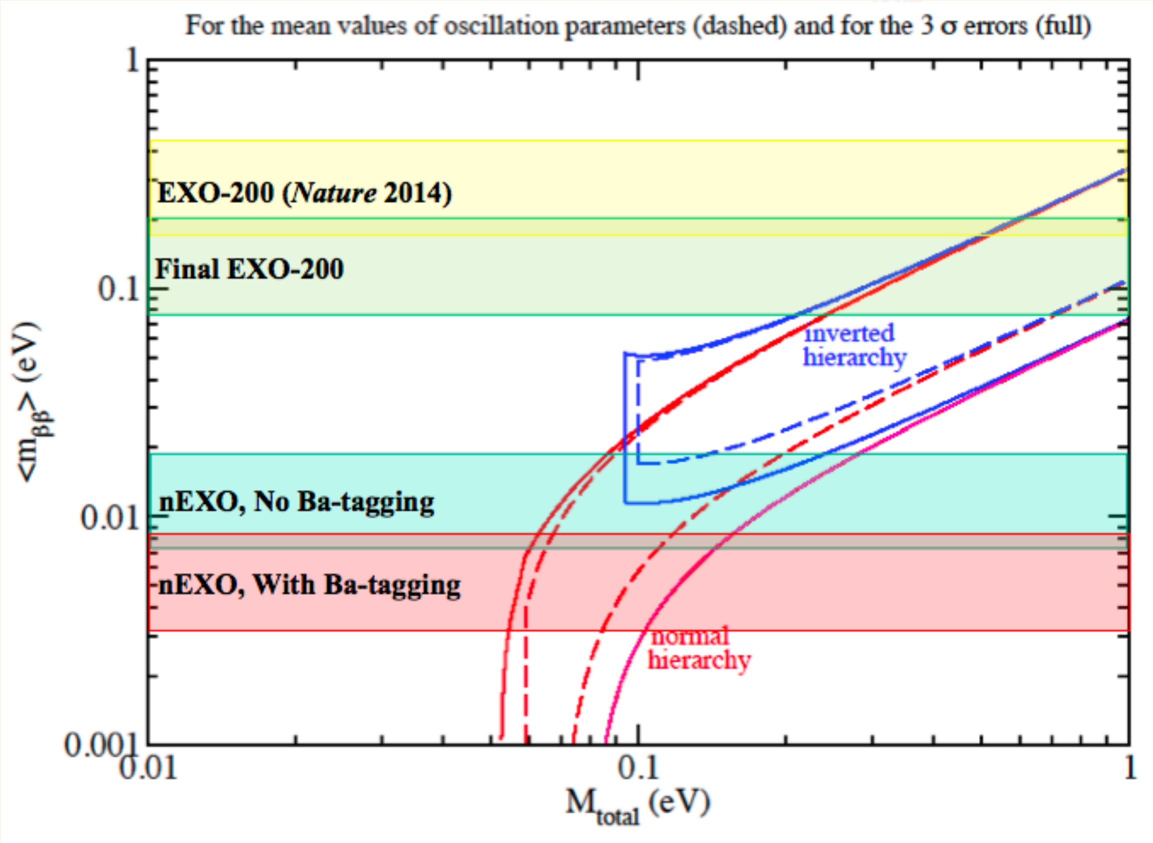
Barium tagging for zero background 0νββ search

$^{136}Xe \rightarrow {}^{136}Ba^{++} + 2e^-$

Barium Tagging: identify barium daughter at 0νββ decay site for complete background elimination



Imaging single Ba atom in solid xenon by nEXO collaboration



How to extract Barium to identify it?

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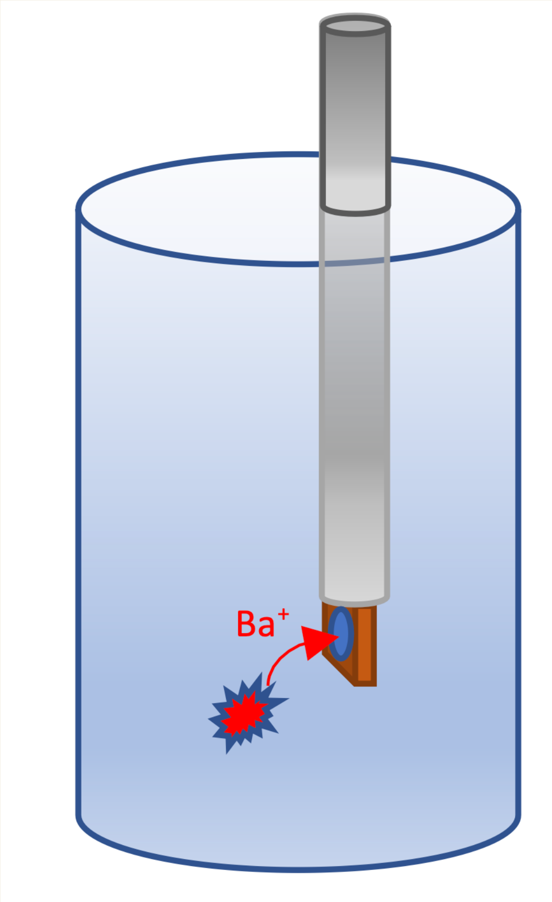
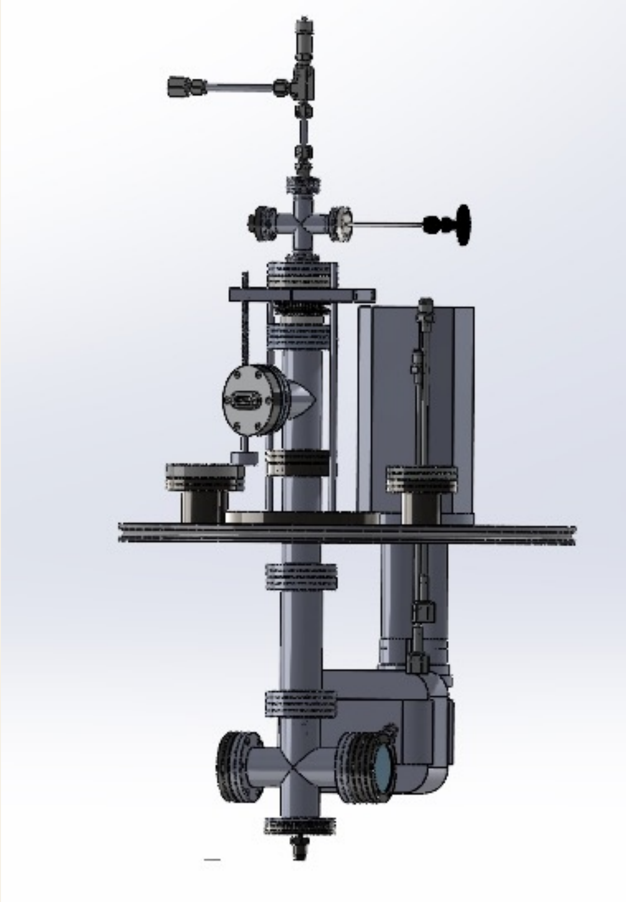
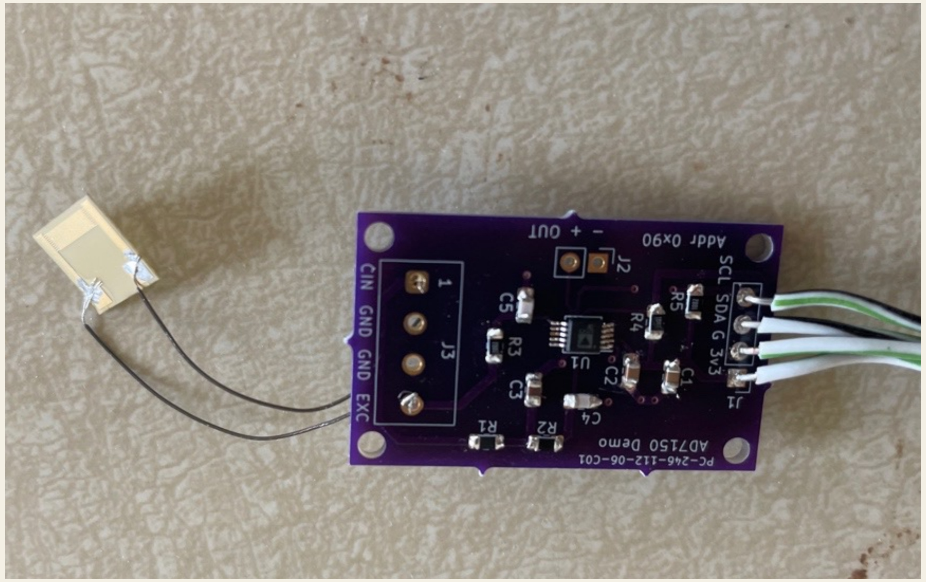
My contribution to R&D of Barium tagging







One scheme is to capture Ba in solid Xe on a cryogenic probe

- Mentored a grad student on design and assembly of a cryogenic probe for xenon freezing
- Designed and built a capacitive xenon ice thickness sensor with 3 µm accuracy

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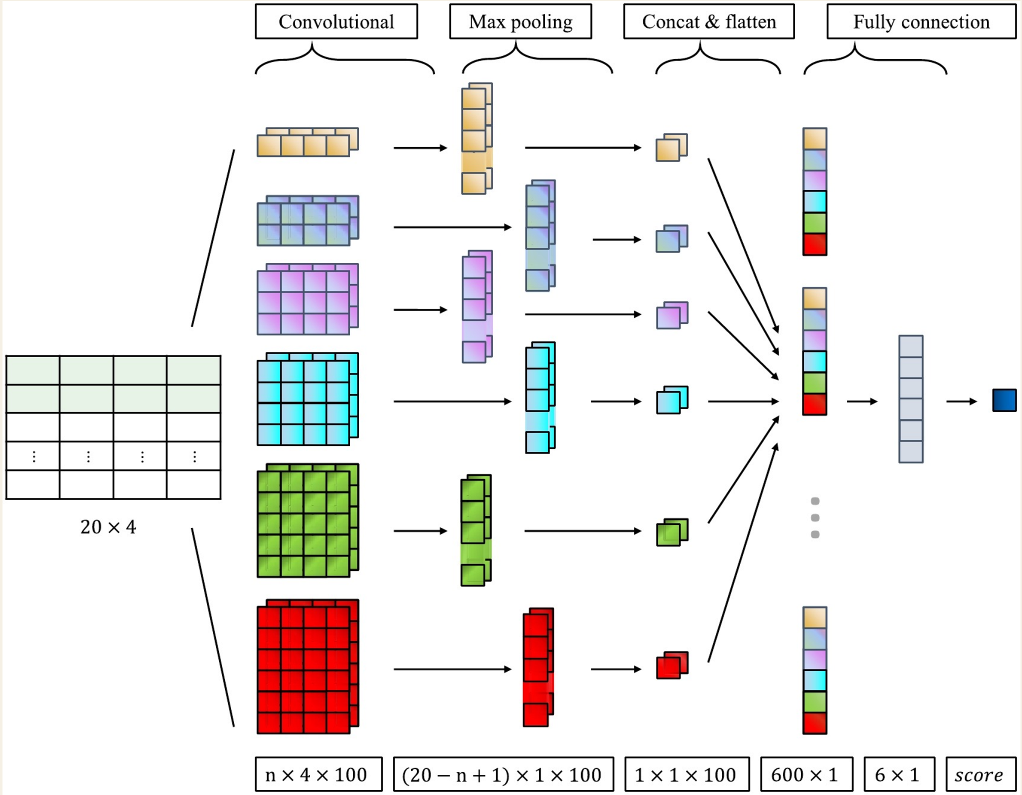
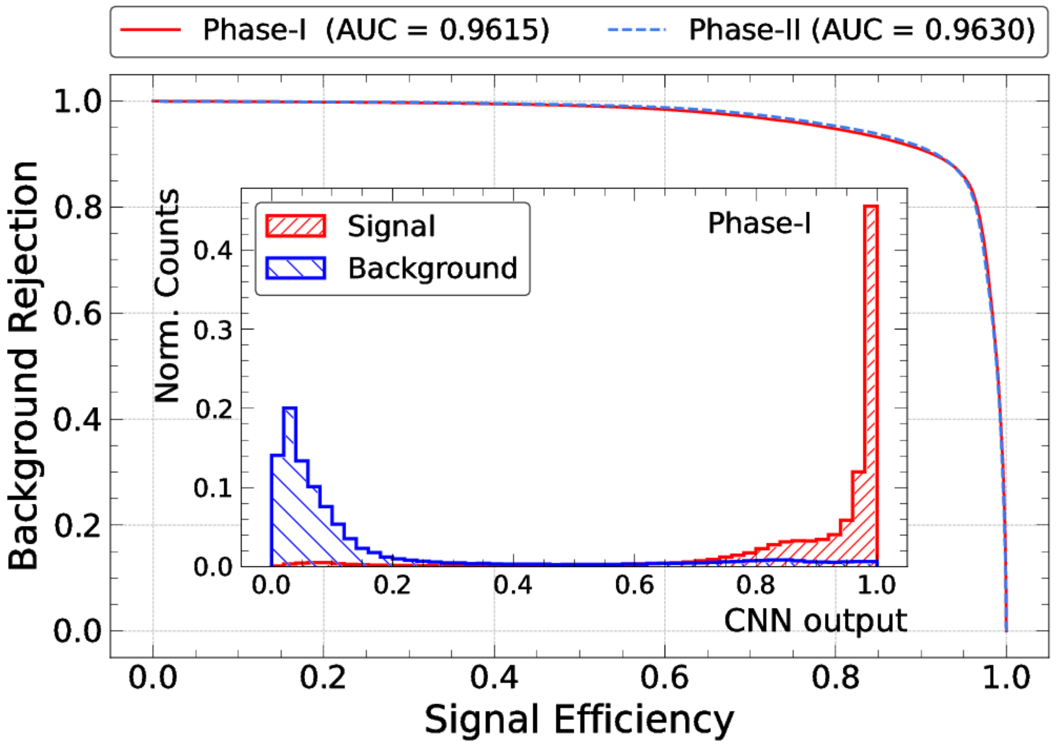
Machine learning applications

ML applications in EXO-200 analyses

Mentored a grad student @IHEP





Chin.Phys.C 47 (2023)

- Search for $2\nu\beta\beta$ of ^{136}Xe to the excited state of ^{136}Ba
- A CNN algorithm to distinguish signal from background using charge cluster information
- Produced world-leading constraint

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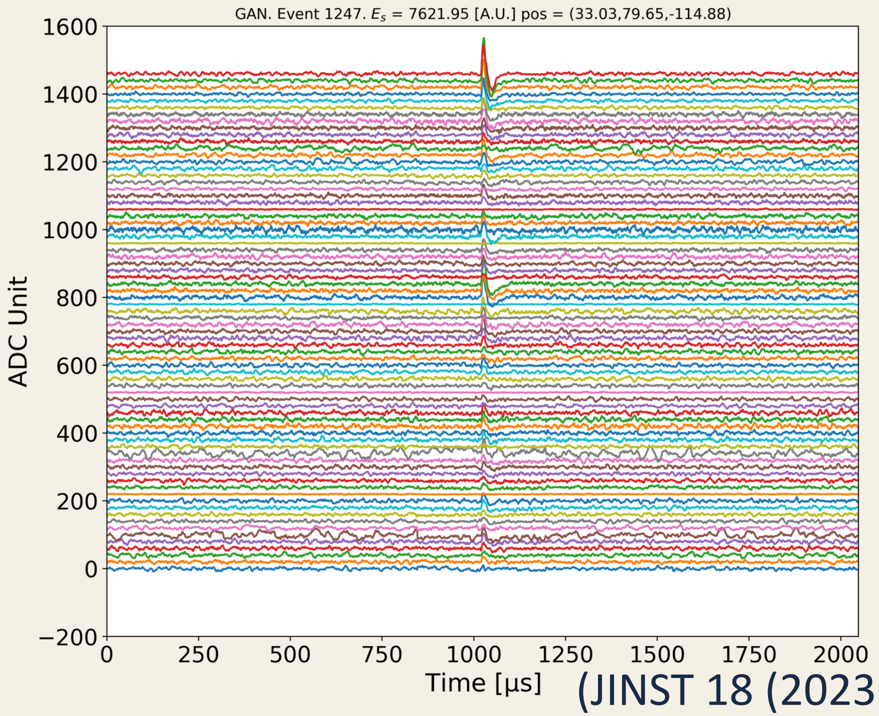
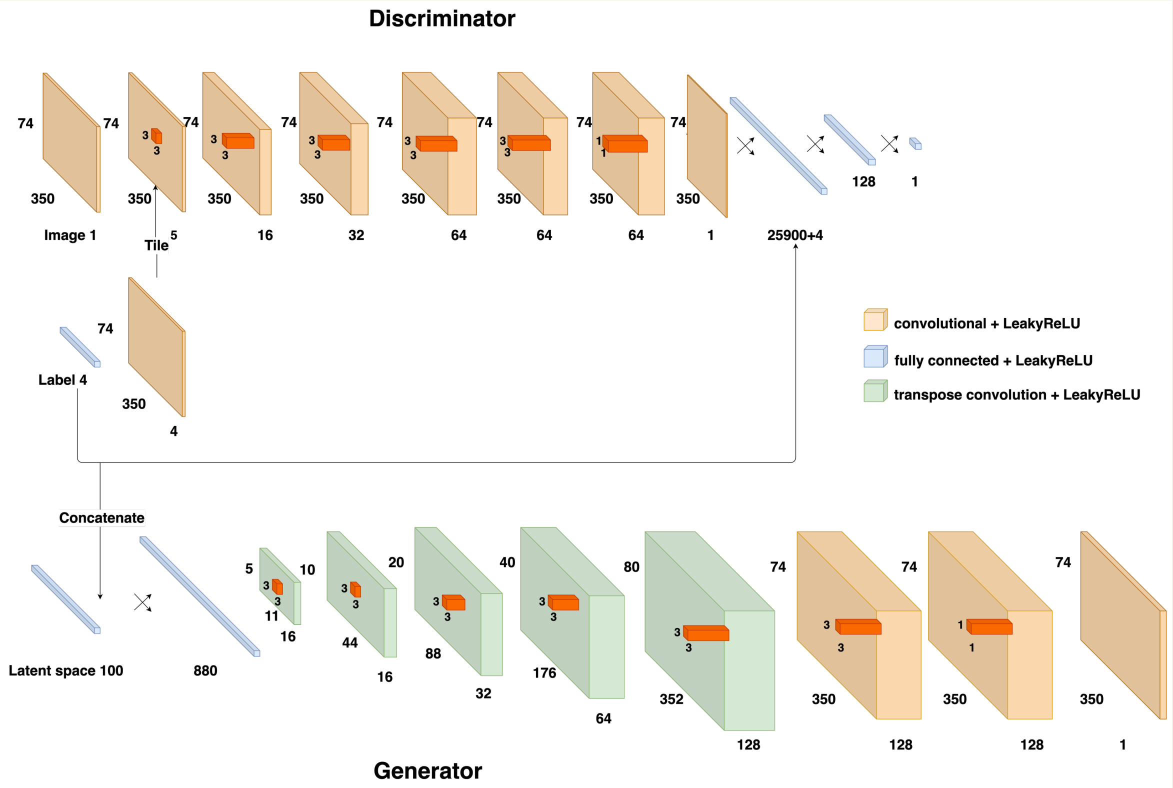
ML applications in EXO-200 analyses

Mentored a grad student @UCSD

Simulated photon detection waveforms



(JINST 18 (2023))



- Generative Adversarial Networks (generator, discriminator, and Wasserstein loss)
- An order of magnitude faster than the traditional simulation
- Reliable simulation trained on calibration data

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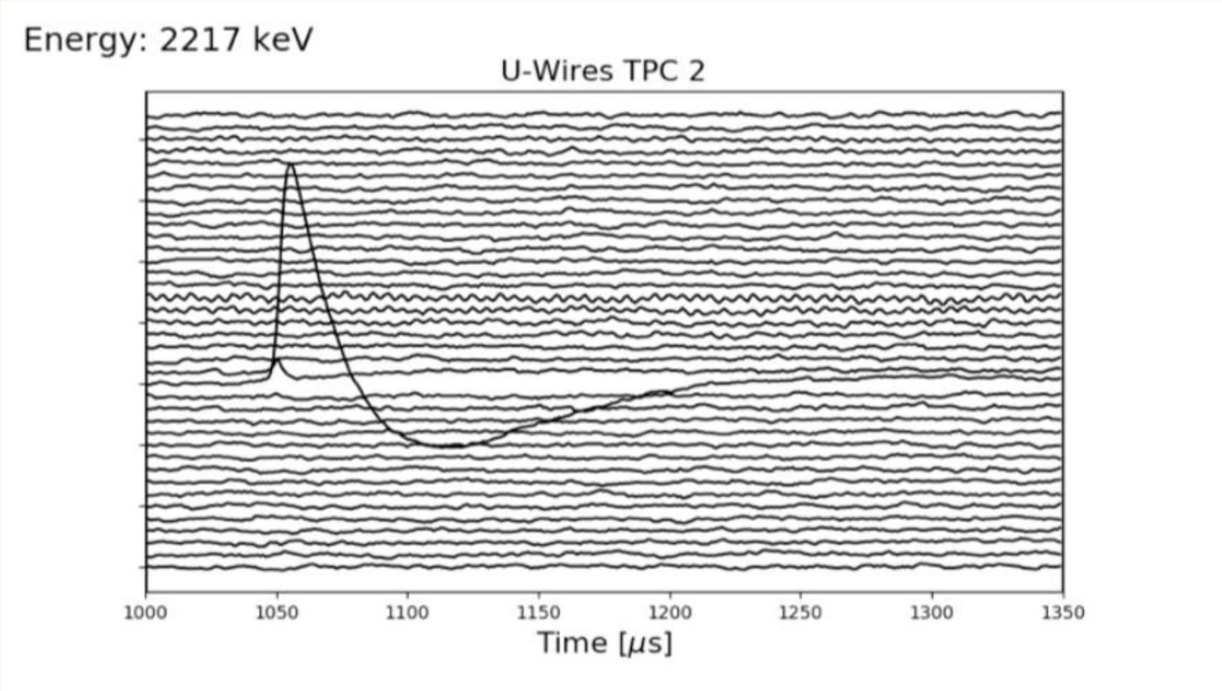
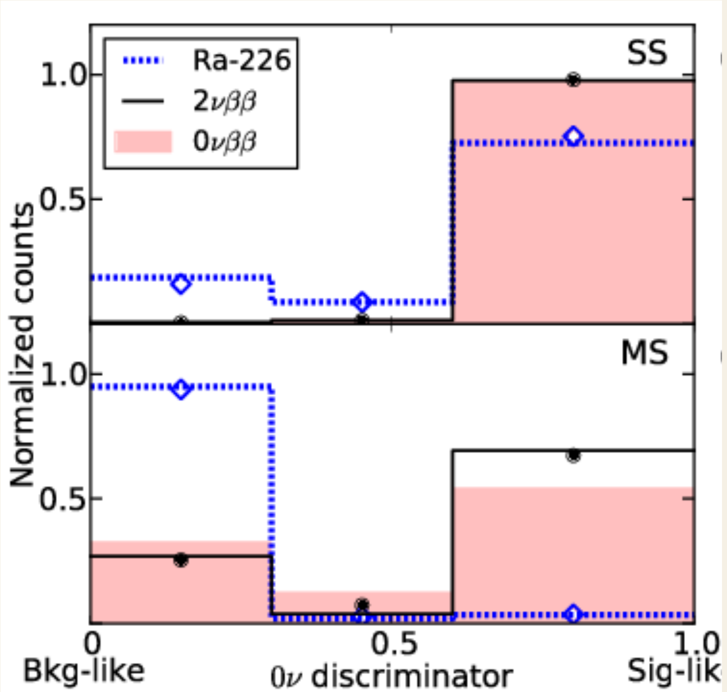
EXO-200 ML data release





- Working with ML experts at UCSD data science institute to release EXO-200 ML dataset
- Open data accessible to physicists and non-physicists for benchmarking ML algorithms and education

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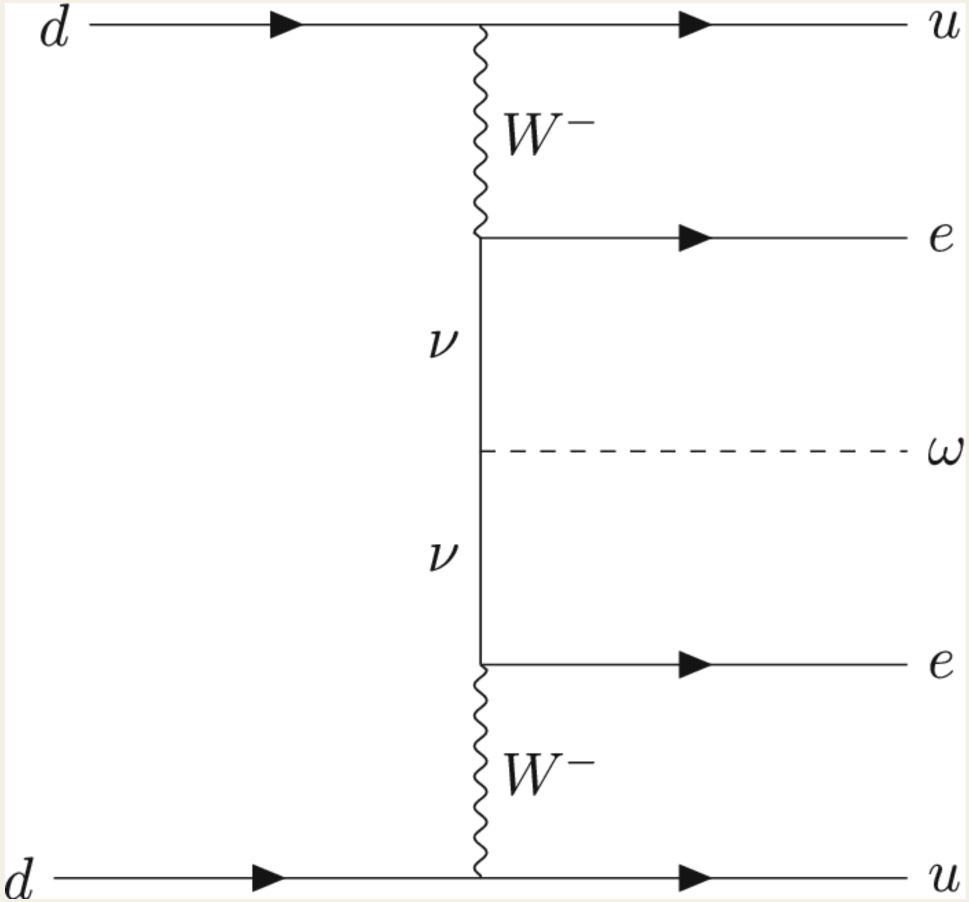
Majoron emitting ββ search



Decay mode	EXO-200 Combined (yr)	$\lvert\langle g_{ee}^M\rangle\rvert$
$0\nu\beta\beta\chi_0 n = 1$	$> 4.3 \times 10^{24}$	$< (0.4 - 0.9) \times 10^{-5}$
$0\nu\beta\beta\chi_0 n = 2$	$> 1.5 \times 10^{24}$	...
$0\nu\beta\beta\chi_0 n = 3$	$> 6.3 \times 10^{23}$	< 0.01
$0\nu\beta\beta\chi_0\chi_0 n = 3$	$> 6.3 \times 10^{23}$	$< (0.3 - 2.5)$
$0\nu\beta\beta\chi_0\chi_0 n = 7$	$> 5.1 \times 10^{22}$	$< (0.3 - 2.8)$
RR	$> 3.7 \times 10^{24}$	...
RL	$> 4.1 \times 10^{24}$	...

Phys. Rev. D **104**, 112002

- World's best limits on the Majoron-emitting decays of ^{136}Xe
- Limit on the coupling constant of $\langle g_{ee}^M\rangle$ is 2 orders of magnitude more stringent than results of pion decay experiments

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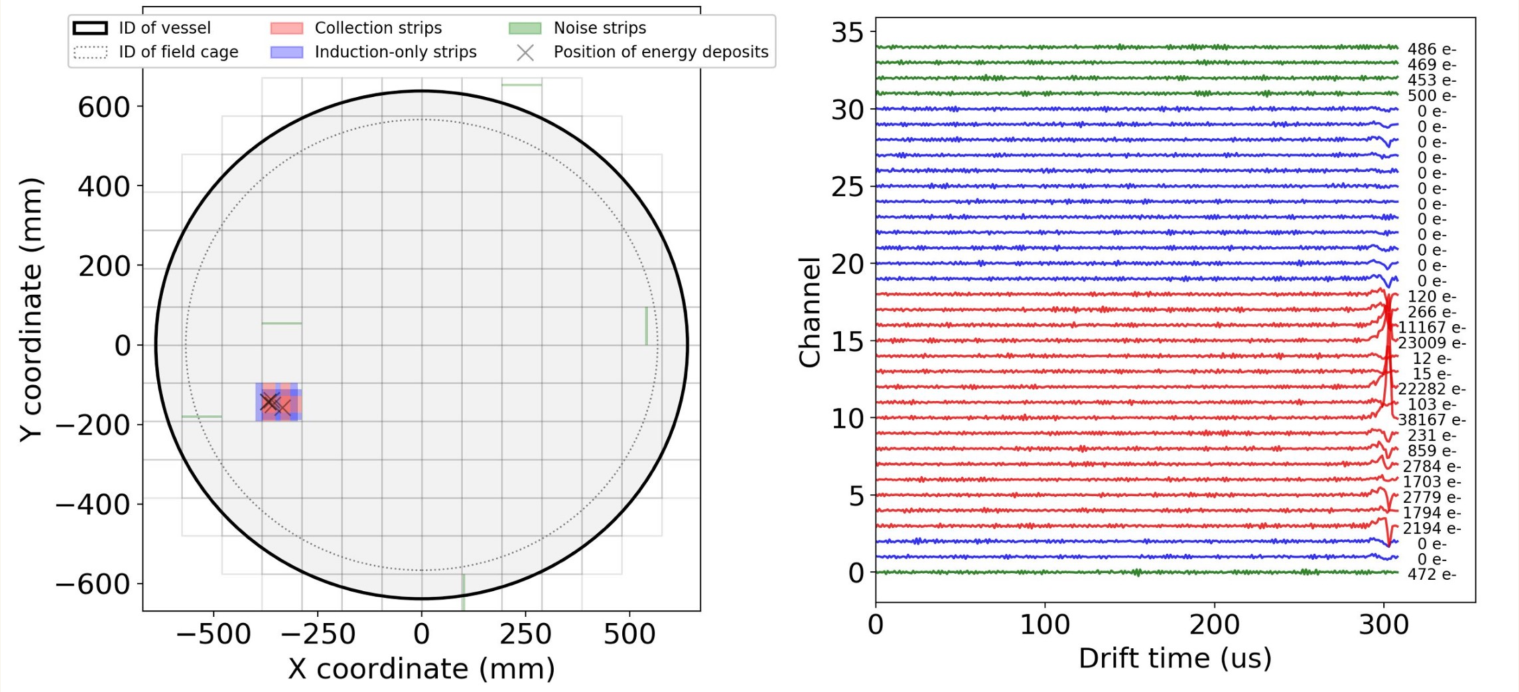
My contribution to R&D of charge readout & ML

Charge simulation of a $0\nu\beta\beta$ event



Developed simulation of charge readout in nEXO that is extensively used in detector design and optimization

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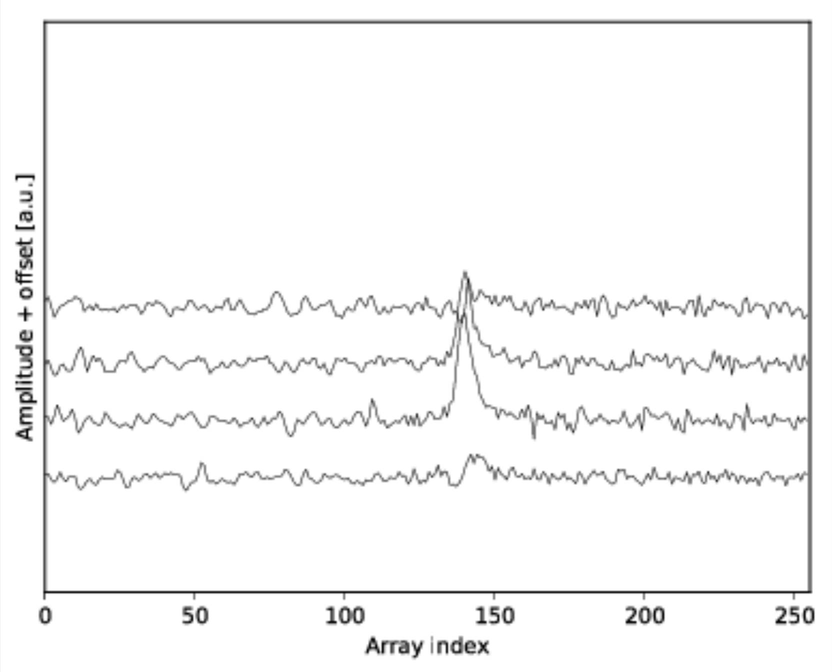
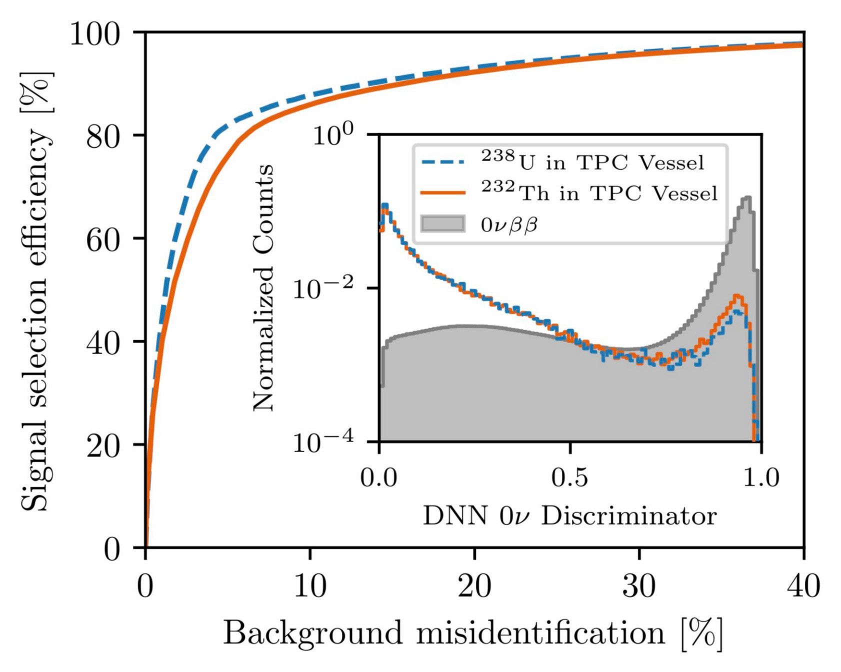
My contribution to R&D of charge readout & ML





Charge readout as a 2D image for CNN input

Developed a ML algorithm to use raw waveforms of charge readout for background rejection, improving the half-life sensitivity for $0\nu\beta\beta$ by ~**30%**

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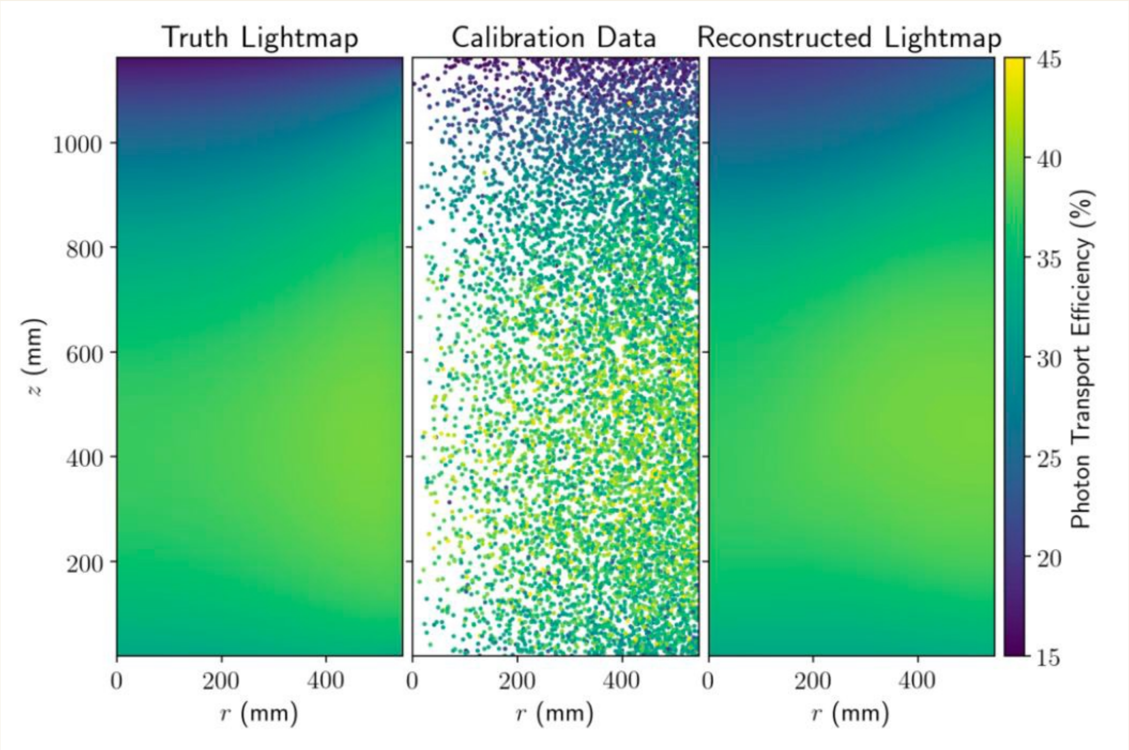
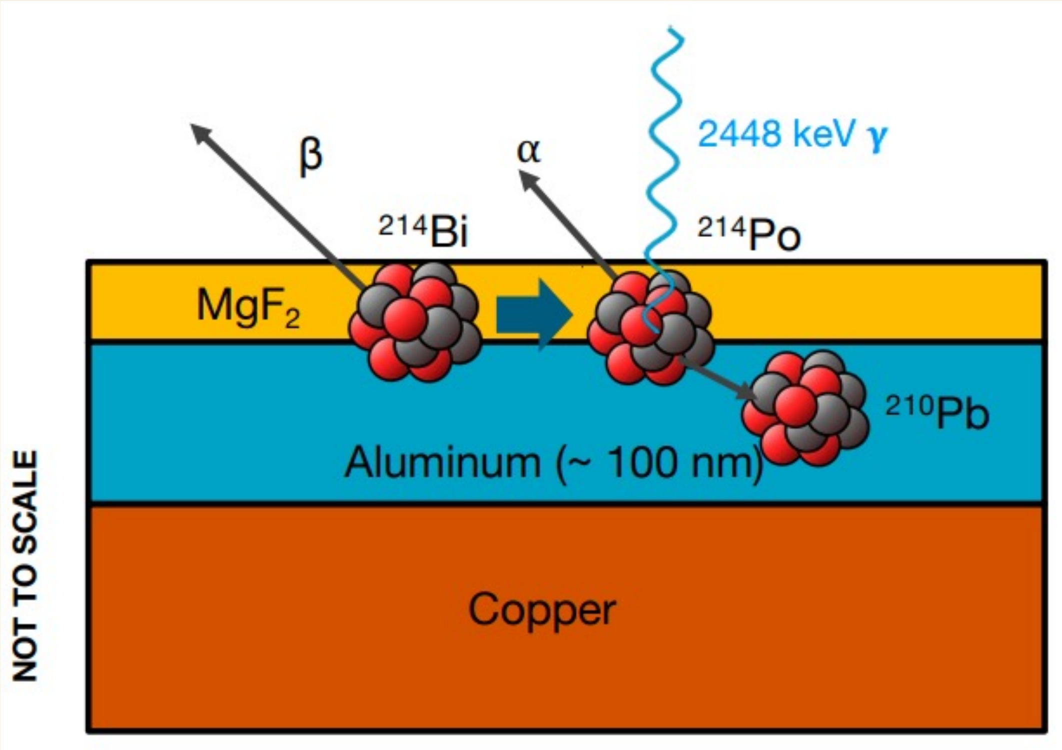
More ML applications in nEXO

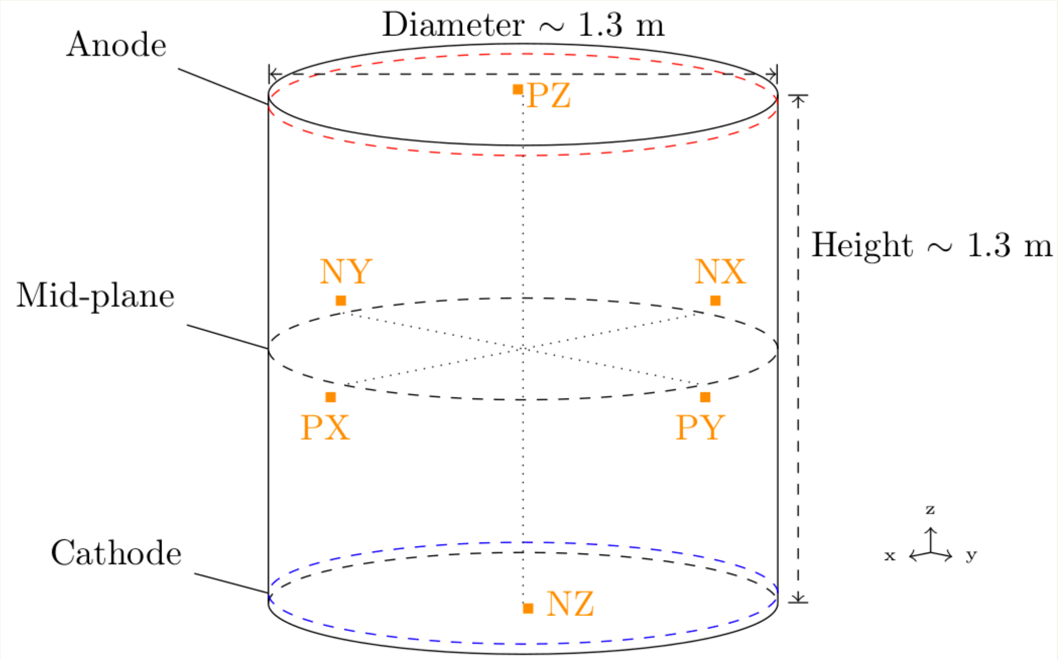




- Add light information to ML input for background rejection
- Accelerate light simulation

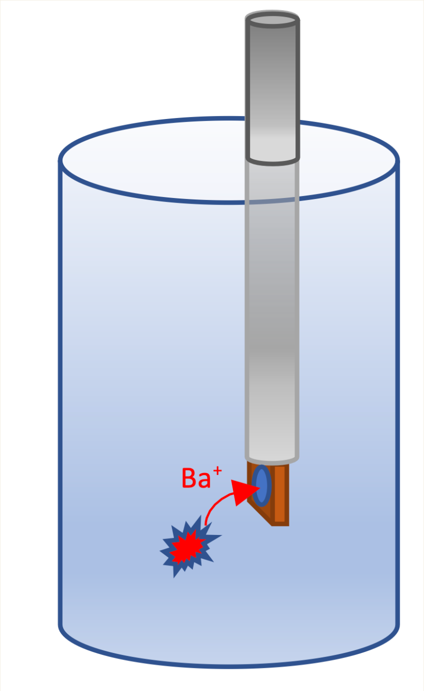
- ML algorithms for radon background rejection for better sensitivity

Fast inference in nEXO



6 different positions (PX, NX, PY, NY, PZ, NZ) marked in orange where sources were placed in the simulation

Calibration event rate: 2000 Hz
Data rate of calibration: ~8 TB/h
Calibration frequency: ~1 h/day
Deep events in inner 1 ton: < 1%



Barium tagging requires fast reconstruction of event energy, position, and topology within ms

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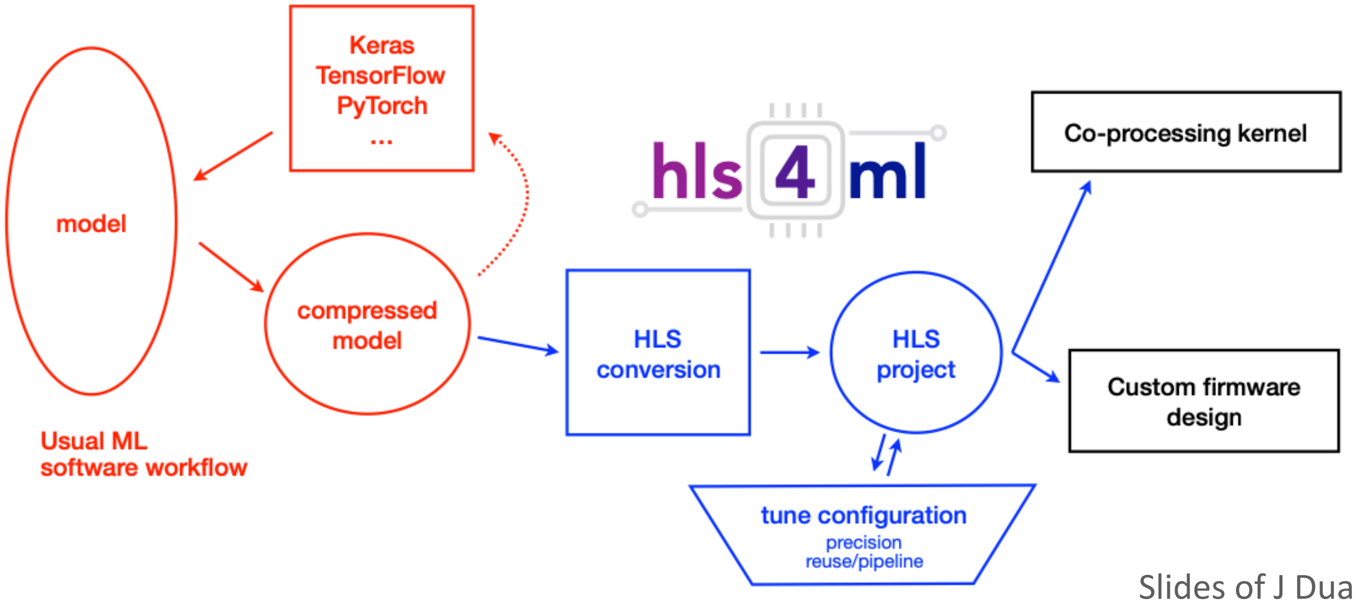
My contribution to R&D of charge readout & ML

- **hls4ml** for physicists or ML experts to translate **ML algorithms** into **FPGA firmware**



Slides of J Duarte

ML implementation on FPGA allows fast event inference

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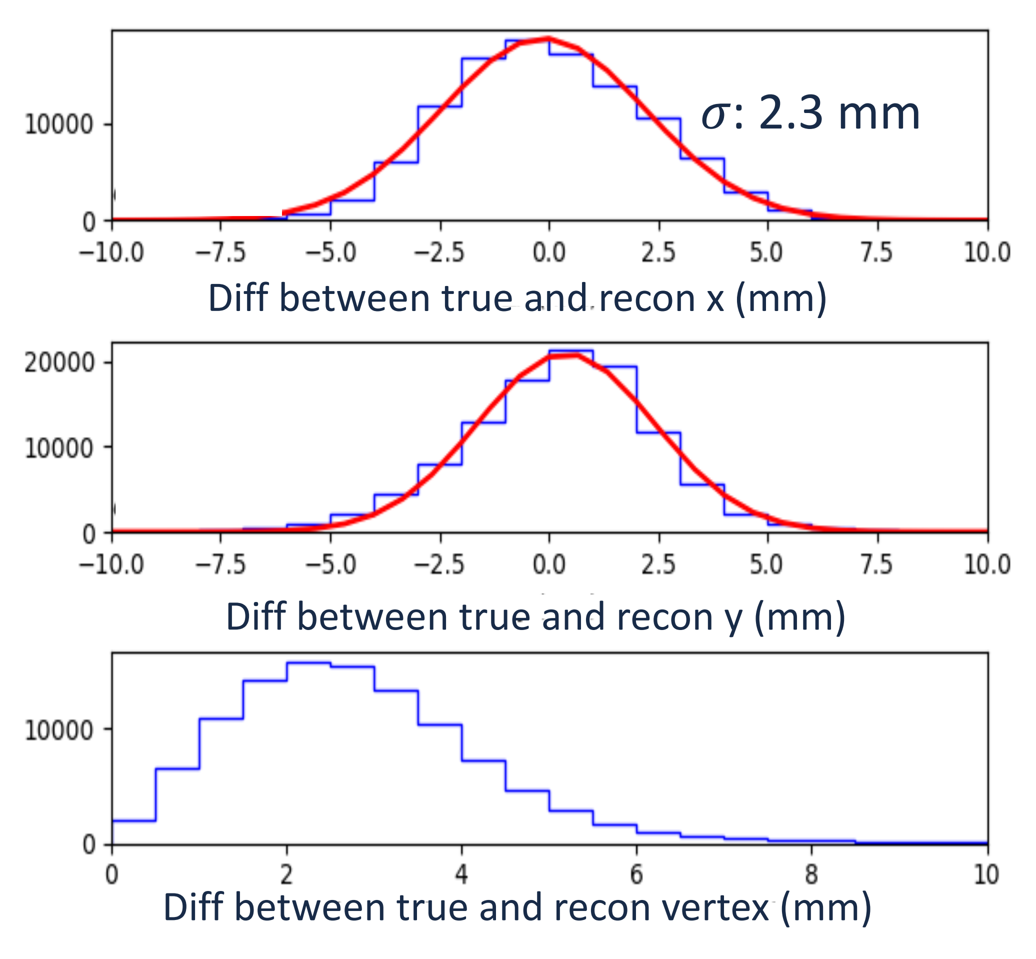
My contribution to R&D of charge readout & ML



Simulated vertex reconstruction resolution of a ML on FPGA

- Trigger of deep events for calibration
  - Real-time vertex recon to select deep events to reduce data (TB/h to 10s GB/h)
- Prompt trigger for Barium tagging
  - Low latency – capture the ion before diffusion
  - High precision – minimize the down time

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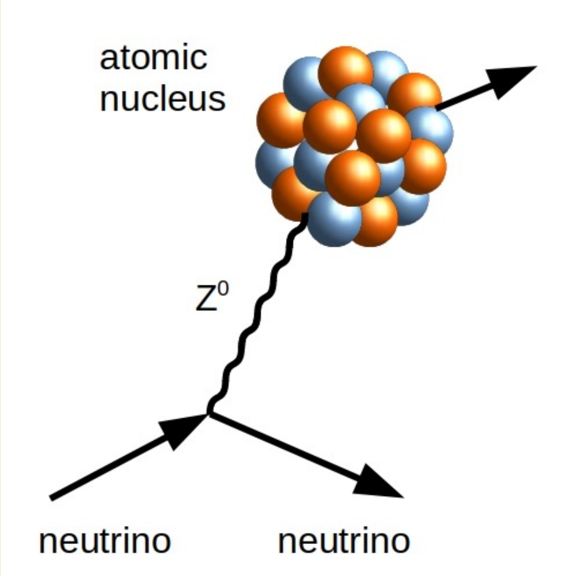
Machine learning applications in EXO-200/nEXO

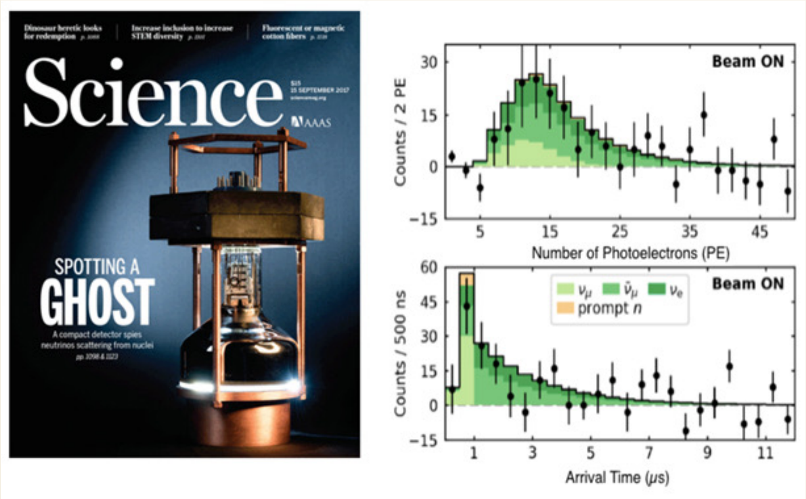
- **Event classification algorithms**: deliver world-leading physics result
- **Event simulation**: complementary to Geant-4 simulation
- **Data release**: publish data for ML benchmarking and education
- **Edge computing**: push ML algorithms to the forefront of DAQ boards

LXeTPC for neutrino detection

NUXE for coherent elastic neutrino nucleus scattering(CEνNS)



CEνNS has been detected before by COHERENT at the Spallation Neutron Source with liquid Argon, CsI, and Germanium.



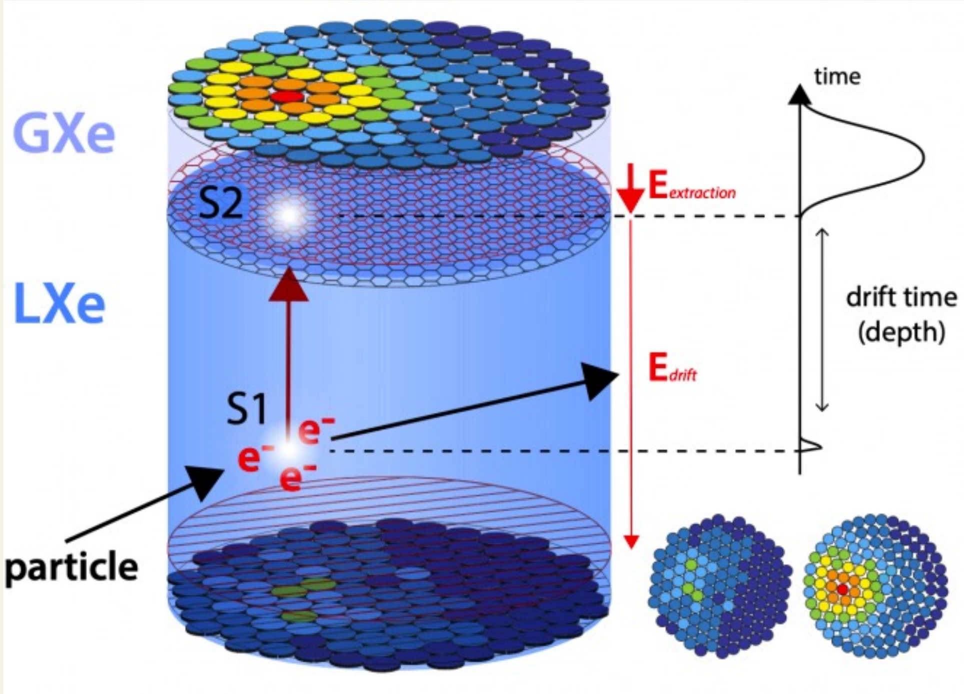


Image credit: XENON Collaboration

Low-threshold detector developed for dark matter search is also capable of detecting ~keV nuclear recoil from CEνNS.

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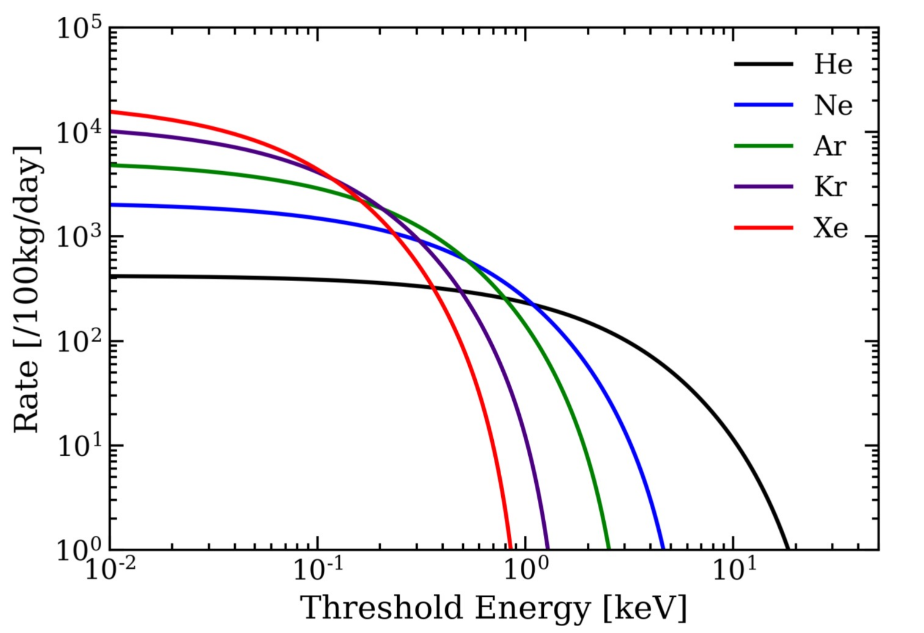
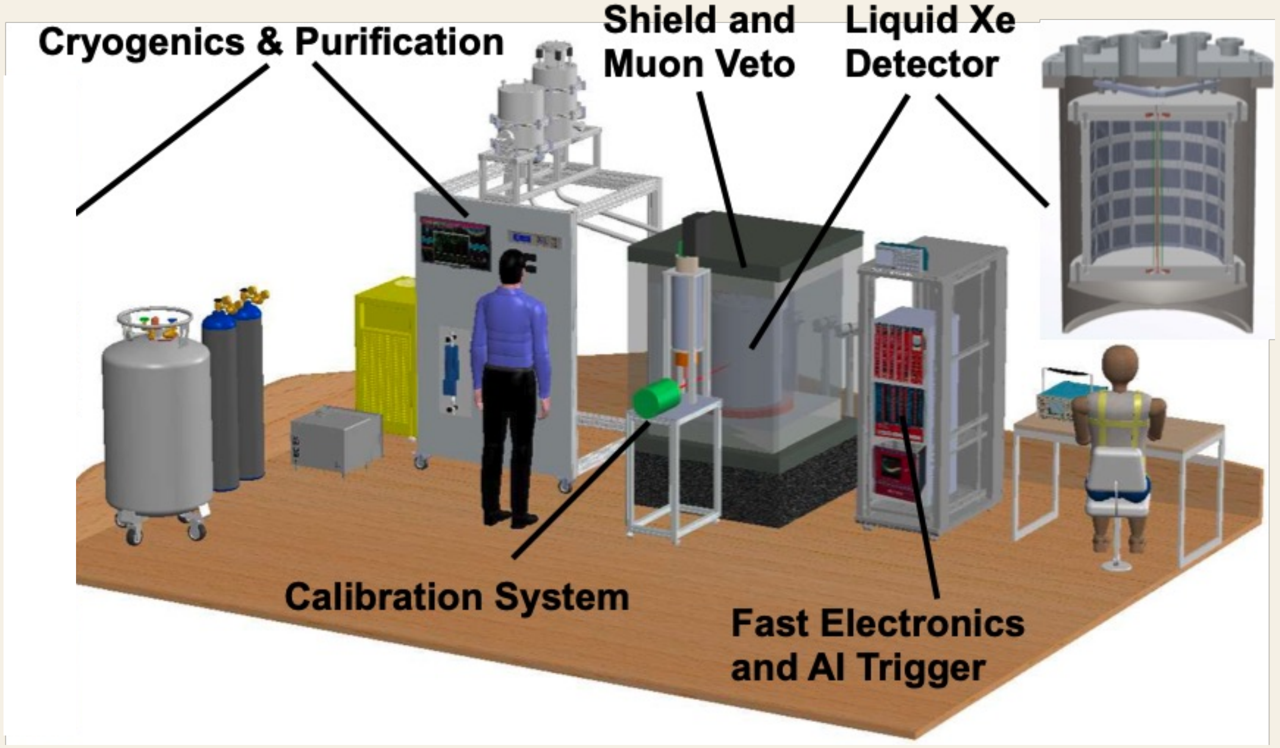
R&D of NUXE at UCSD



Calculated CEνNS rates in different elements from reactor anti-neutrinos with a flux of $6.3\times10^{12}\mathrm{cm}^{-2}\mathrm{s}^{-1}$



NUXE: compact and movable LXe detector with $O(10\sim100)$ kg active target mass and single-electron sensitivity.

- Detection of CEvNS from reactor neutrinos allows precise test of the Standard model and study of neutrino properties
- Application in nuclear security

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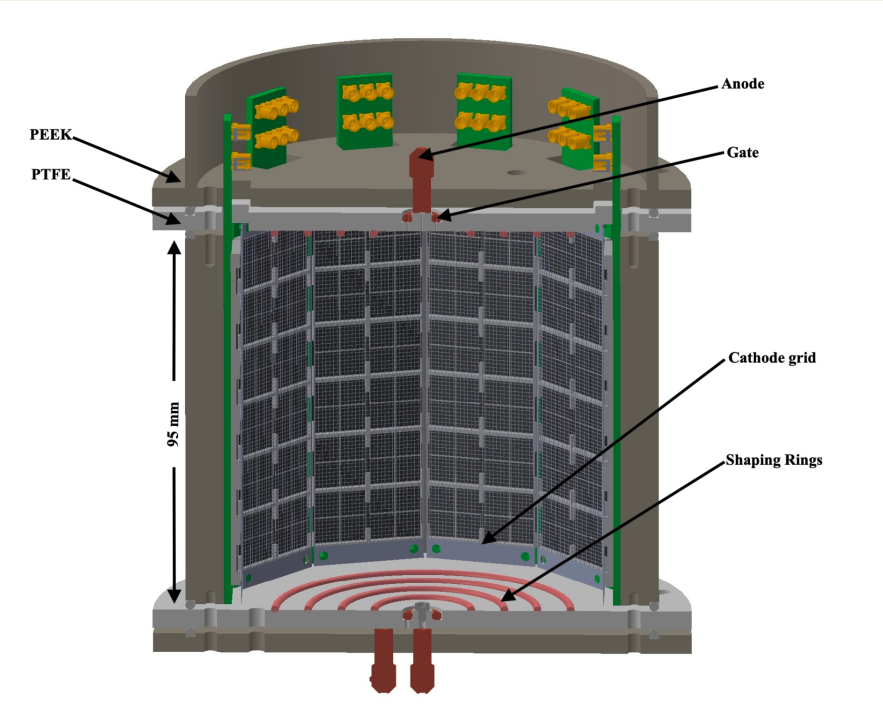
My contributions to NUXE



- Advised grad students on cryogenic system assembly and slow control
- Designed and built a purity monitor to measure e^- lifetime of ~10 ms
- Advised students on SiPM photon readout in a prototype detector

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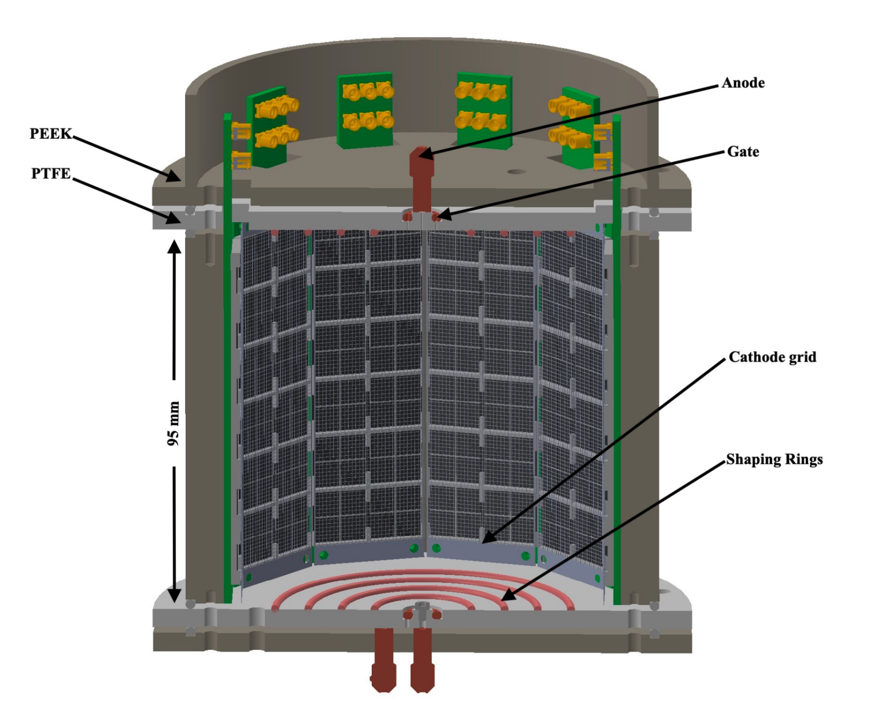
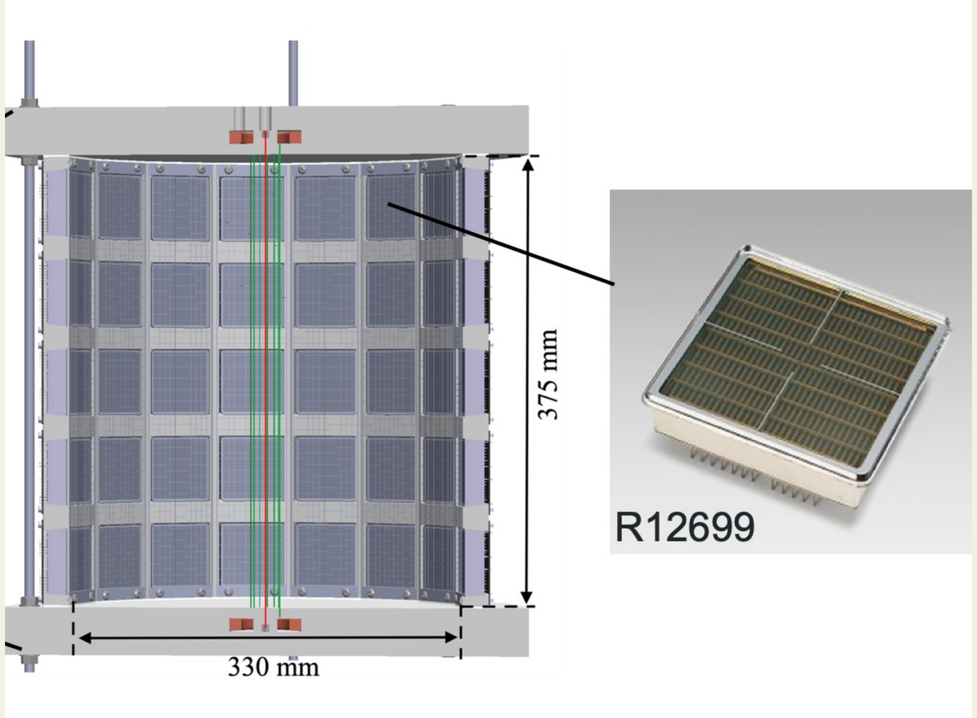
Fast trigger need in NUXE



24 channels in small prototype



~100 channels, 500 MS/s, 14 bit

We aim to develop AI trigger system for NUXE DAQ

Next-generation noble liquid detectors

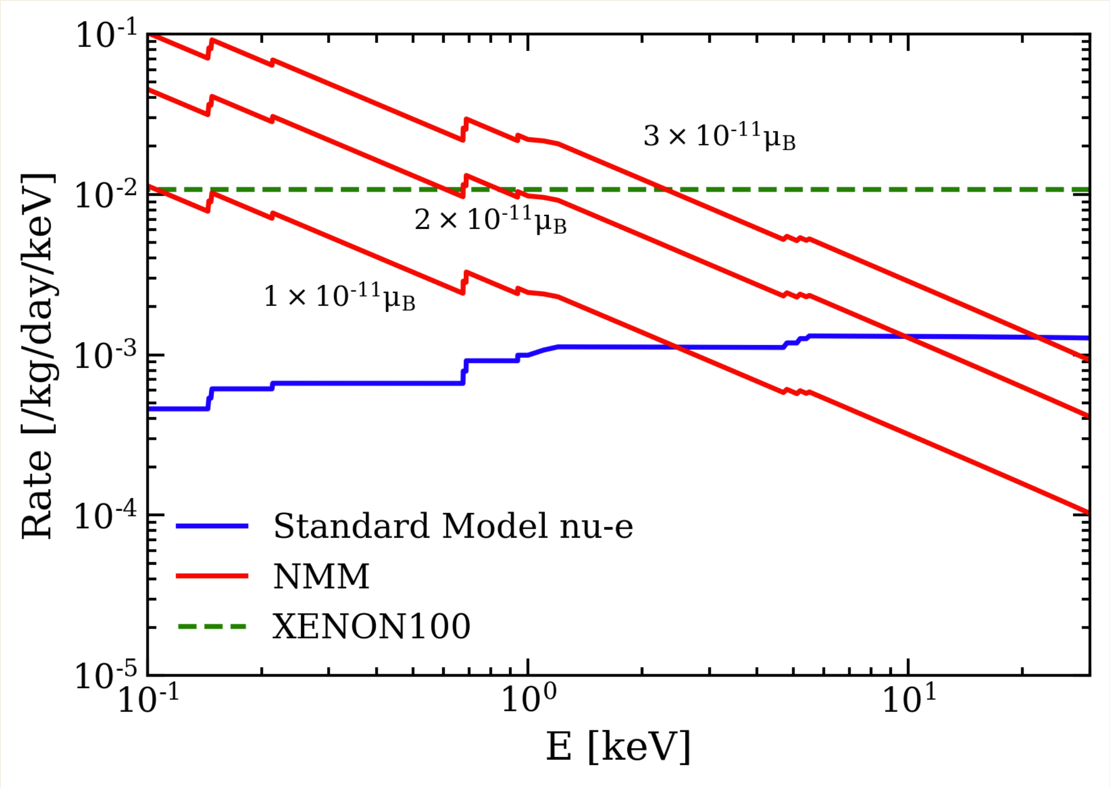
- Advanced instrumentation
  - Cryogenic and ultra-low background readout
  - New photodetectors (SiPM)
- ML techniques
  - Deliver world-leading result
  - Push ML to the forefront DAQ

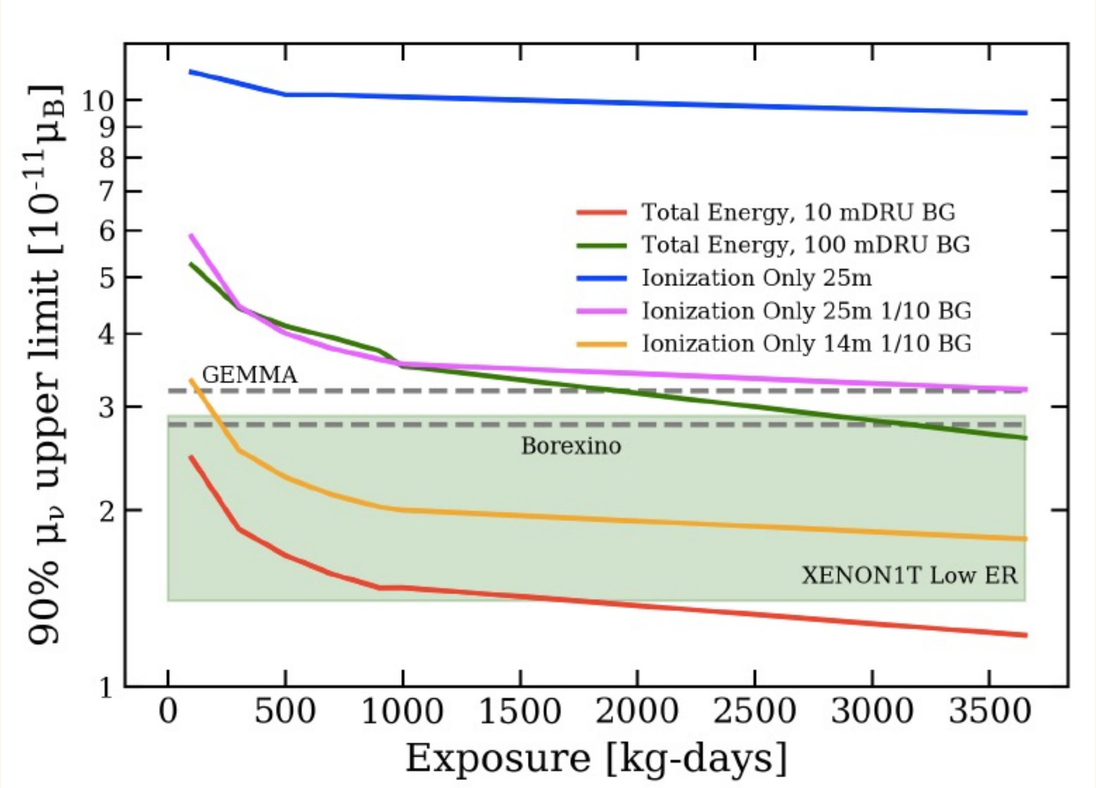
The combination of advanced instrumentation and ML will push the physics reach of noble liquid detectors!

Backup

NUXE sensitivity

Universe 2021, 7, 54





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